

**Bond University**

## **MASTER'S THESIS**

**Effect of thermal strain on training and performance in elite athletes.**

Wijekulasuriya, Gyan

*Award date:*  
2022

[Link to publication](#)

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.



**BOND  
UNIVERSITY**

Effect of thermal strain on training and performance in elite  
athletes

Gyan Wijekulasuriya

Submitted in total fulfilment of the requirements of the degree Master of  
Science by Research (Health Sciences)

June 2021

Faculty of Health Sciences and Medicine

Primary Supervisor: Associate Professor Vernon Coffey

Associate Supervisor: Associate Professor Gregory Cox

*This research was supported by an Australian Government Research Training Program Scholarship*

## **Abstract**

The impact of specific environmental conditions on training and competition performance is dependent on the nature of the thermal stress and the mode, duration and intensity of exercise. The effect of the environment contributes to the variation in human performance and can negatively impact physical work capacity of athletes. Moreover, quantifying the physiological and performance responses of athletes to varied environmental conditions during competition simulations and training provides important information for sport scientists and coaches to develop appropriate strategies to minimise sub-optimal performance. Whilst the effect of divergent environmental conditions on cycling and running performance have been well characterised, the effect on swimming performance is poorly defined. Mitigating detrimental effects of the environment on human performance may also be promoted using ergogenic aids. Per-cooling strategies, such as acetaminophen ingestion, have been proposed to reduce thermal strain during endurance sports such as Olympic distance triathlon, but the effect of acetaminophen has not been tested in trained endurance athletes. Therefore, the aims of the studies undertaken for this applied sport science thesis were to quantify the thermoregulatory and performance responses to (1) differing environmental conditions during training (swimming) and (2) acetaminophen ingestion under heat stress during endurance competition simulation (triathlon/cycling).

The first experimental study (Chapter 2) aimed to determine the effect of different environmental conditions on physiological and perceptual measures and training performance during outdoor swim training in elite and sub-elite swimmers. The hypothesis was that core and skin temperature and thermal sensation would be reduced during outdoor swimming in colder environmental conditions and would be associated with poorer training performance. Nine elite and ten sub-elite swimmers undertook outdoor swim training in a 50m heated pool

in COOL (wet bulb globe temperature [WBGT]  $14.7 \pm 0.4$  °C) and WARM (WBGT  $23.0 \pm 0.2$  °C) or COLD (WBGT  $10.3 \pm 1.8$  °C) and HOT (WBGT  $27.0 \pm 3.3$  °C) environmental conditions, respectively. On each occasion matched training sessions were undertaken with a total swimming distance range of 5.6-6.9 km including three  $\times$  100 m efforts repeated 4 to 6 times completed by elite swimmers, whilst sub-elite swimmers completed 4.6-7.5 km with eight  $\times$  50 m sprints. Ambient temperature differed between COOL and WARM ( $\Delta T_a$  7.9 °C,  $p < 0.001$ ), and COLD and HOT ( $\Delta T_a$  14.5 °C,  $p < 0.001$ ). Skin temperature (Elite  $\Delta T_{sk}$   $2.8$  °C  $\pm 0.5$ ,  $d = 5.1$ ; Sub-elite  $\Delta T_{sk}$   $4.5$  °C  $\pm 1.0$ ,  $d = 4.5$ ;  $p < 0.001$ ) and thermal sensation (Elite WARM:  $4.6 \pm 0.4$  AU; COOL:  $4.2 \pm 0.8$  AU,  $p = 0.006$ ; Sub-Elite HOT:  $4.8 \pm 0.3$  AU; COLD:  $4.2 \pm 0.6$  AU,  $p = 0.028$ ) were higher in WARM/HOT conditions compared to COOL/COLD but core temperature was not different. There were small improvements in swimming performance during WARM/HOT trials in elite and sub elite swimmers (Elite: 0.8-4.6%,  $d = 0.2$ -0.3; Sub-Elite: 2.3-4.8%,  $d = 0.3$ -0.6). Overall, skin temperature and thermal sensation vary dependent on ambient temperature during swimming despite consistent water temperature, with a small to moderate improvement in the quality of swim training during hot/warm compared to cold/cool seasonal conditions.

In the second experimental study, the aim was to determine the effect of acetaminophen (paracetamol) ingestion on physiological and perceptual measures during steady state cycling and time trial cycling performance of trained triathletes in hot and humid conditions. The hypothesis was that acetaminophen ingestion would decrease core temperature and thermal sensation and improve performance during an endurance cycling time-trial in the heat. In a randomised, double-blind crossover design, thirteen triathletes (4 female) completed ~60 min steady state cycling at 63% peak power output followed by a  $7\text{kJ}\cdot\text{kg}^{-1}\cdot\text{BM}^{-1}$  time trial in hot and humid conditions 90 minutes after consuming either a  $20\text{mg}\cdot\text{kg}^{-1}\cdot\text{BM}^{-1}$  dose acetaminophen (ACT) or a colour-matched placebo (PLA) (ACT,  $29.9 \pm 0.7$  °C,  $68.7 \pm 2.7\%$

relative humidity [RH]; PLA,  $29.7 \pm 0.7$  °C,  $68.7 \pm 2.8\%$  RH). In the ACT time trial, there was a moderate but not significant *increase* in time to completion ( $64.6 \pm 112.7$  s,  $d = 0.57$ ,  $p = 0.086$ ) and there was no difference in core temperature, skin temperature, thermal sensation, thermal comfort or fluid balance between conditions. Therefore, acetaminophen is not an effective ergogenic aid during endurance exercise in hot and humid conditions and existing heat mitigation strategies should be used during endurance competition.

In summary, the studies undertaken for this thesis provide novel information on the interaction between the thermoregulatory response and training, and competition performance in swimming and endurance cycling, respectively. Cold conditions appear to suppress sprint swimming performance and heat storage during endurance exercise in hot and humid conditions cannot be off set through acetaminophen ingestion. The studies in this thesis emphasise the importance of testing the effect of environmental conditions and ergogenic aids on the physiology and performance of athletes during exercise bouts with high external validity. Continued exploration of strategies that manipulate the thermal response to varied environmental conditions will assist sport scientists and coaches to optimise training and competition performance.

## **Keywords**

Thermoregulation, Olympic distance triathlon, swimming, sprint performance, endurance cycling, environmental conditions, heat stress

## **Declaration By Author**

This thesis is submitted to Bond University in fulfilment of the requirements of the degree Master of Science by Research (Health Sciences).

I declare that the research presented within this thesis is a product of my own original ideas and work and contains no material which has previously been submitted for a degree or diploma at this university or any other institution, except where due acknowledgement has been made.

Gyan Wijekulasuriya

24/06/2021

## **Ethics Declaration**

The research associated with this thesis was conducted on human participants and received ethics approval from the Bond University Human Research Ethics Committee, ethics application number GW02856 and GW02854.

## Acknowledgements

They say it takes a village to raise a child and my village has supported me unreservedly throughout my candidature. I am grateful for the encouragement of all who showed interest in my thesis however a select few have significantly helped me complete these studies over the past two and half years and I would like to highlight their efforts.

Firstly, thank you to my primary supervisor Vernon Coffey without whom I would not have finished this thesis. Your measured approach, high standards and unwavering support is unmatched, and I am humbled by the time and care you have taken to develop my research skills. You have been an outstanding role model and I feel privileged to have worked alongside you. Similarly, it was an honour to work with Gregory Cox whose dietetics expertise and research experience contributed substantially towards this thesis. Coxy, thank you for teaching me how to run an organised laboratory, for your continual belief in my abilities and for the surplus of Mars bars and other tasty snacks around the research office.

This thesis would not have been possible without the financial and in-kind support of the Queensland Academy of Sport, Swimming Australia and Triathlon Australia including, but not limited to, the personal exertions of Dr Tom Vandenberg, Dr Avish Sharma and Dr Simon Pearson. Thank you for giving me access to the programs, athletes and coaches you work with and helping facilitate those relationships.

To the coaches of the TSS Swimming squad, specifically Chris Nesbitt and Dr Adam Mallett, thank you for being so accommodating and making your high-performance squad available for our swimming study. Likewise, to Dan Atkins (Triathlon Australia) thank you for collaborating with us and making your athletes available for our triathlon simulation study. To the athletes involved in both studies, thank you for your exertions, compliance and enthusiastic participation. It was a pleasure to work with you.



The collegiality and advice of the HDR students and staff at Bond University especially at the Bond Institute of Health and Sport kept me focused and motivated. Thank you to Luke Badham, Fergus O'Connor, Lisa Wächtler, Jessica Farley, Ben Hindle, Danny Maupin, Amy-Lee Bowler and Josh Whitty who were always in the HDR office and supportive of my endeavours. Thankyou specifically to Luke, Fergus, Lisa and Amy-Lee and students Ashleigh Keefe, James Kleidon, Anna Atkinson and Mikayla De Castro who helped collect data during my thesis.

Any thesis is completed within a global context however my thesis was uniquely started before and completed during the COVID-19 pandemic. I would like to acknowledge the efforts of the Australian public, healthcare and essential workers who all contributed and continue to contribute to the effective management of the pandemic in Australia. Without their efforts, these studies would not have been realised.

To my friends who rode the ups and downs with me and provided many laughs, listened to my qualms and kept me grounded, thank you for being there whenever I needed a day, night or week away from the office.

Finally, thank you to my family for being the incredible people you are and for supporting me unconditionally during a challenging time for us. Mum, your advice is unparalleled and your constant pursuit of excellence inspires me. Dad, you taught me to be humble, kind and to work hard, advice which has served me well. Manisha and Shalini, your interest in my research from afar and escapades at home keep me sane, never change. I hope this work makes you all proud.

## Table of Contents

Preface	
Abstract .....	ii
Keywords .....	iv
Declaration By Author .....	v
Ethics Declaration .....	vi
Acknowledgements .....	vii
List of Tables .....	xiii
List of Figures .....	xv
List of Equations .....	xviii
Abbreviations .....	xix
<b>Chapter 1 Literature Review .....</b>	<b>1</b>
1.1 Overview: Athletic Performance and Thermoregulation .....	2
1.2 Current and Future Environmental Challenges for Athletes .....	5
1.3 Effect of Thermoregulatory Stress on Human Physiology .....	13
1.3.1 Hot Conditions .....	13
1.3.2 Cold Conditions .....	16
1.4 Effect of Thermoregulatory Stress on Human Performance .....	22
1.4.1 Running .....	22
1.4.2 Cycling .....	25
1.4.3 Swimming .....	32
1.5 Ergogenic Aids for Exercise in the Heat .....	34
1.5.1 Pre-Cooling .....	36
1.5.2 Per-Cooling .....	38

1.6 Summary and Aims of this Thesis .....	43
1.6.1 Aims and Hypotheses.....	43
<b>Chapter 2 Effect of varied environmental conditions on thermoregulation and outdoor training performance of elite and sub-elite swimmers .....</b>	<b>45</b>
2.1 Abstract .....	46
2.2 Introduction.....	47
2.3 Methods.....	49
2.3.1 Participants .....	49
2.3.2 Experimental Overview.....	50
2.3.3 Preliminary testing .....	50
2.3.4 Testing Procedures Overview .....	51
2.3.5 Dietary Standardisation .....	54
2.3.6 Environmental Conditions.....	54
2.3.7 Performance Times .....	54
2.3.8 Gastrointestinal Temperature .....	55
2.3.9 Skin Temperature .....	55
2.3.10 Perceptual Measures.....	58
2.3.11 Fluid Balance.....	58
2.3.12 Statistical Analyses .....	58
2.3 Results.....	60
2.3.1 Environmental Conditions.....	60
2.3.2 Performance .....	62
2.3.3 Gastrointestinal Temperature .....	64
2.3.4 Mean Skin Temperature .....	66
2.3.5 Thermal Sensation and Comfort .....	68

2.3.6 Fluid Balance.....	72
2.4 Discussion .....	74
<b>Chapter 3 Effect of acetaminophen on steady state and time trial cycling performance in endurance trained triathletes in hot and humid conditions.....</b>	<b>79</b>
3.1 Abstract .....	80
3.2 Introduction.....	81
3.3 Methods.....	83
3.3.1 Participants .....	83
3.3.2 Experimental Overview.....	84
3.3.3 Preliminary Testing .....	84
3.3.4 Dietary Standardisation .....	87
3.3.5 Environmental Conditions.....	87
3.3.6 Steady State and Time Trial Cycling .....	87
3.3.7 Gastrointestinal and Skin Temperature .....	88
3.3.8 Heart Rate.....	89
3.3.9 Perceptual Measures.....	90
3.3.10 Fluid Balance.....	90
3.3.11 Statistical Analyses .....	91
3.4 Results.....	92
3.4.1 Performance .....	92
3.4.2 Gastrointestinal Temperature, Skin Temperature and Heart Rate .....	94
3.4.3 Rating of Perceived Exertion, Thermal Sensation and Thermal Comfort .....	96
3.4.4 Fluid Balance.....	98
3.5 Discussion .....	99
<b>Chapter 4 Summary and Conclusion.....</b>	<b>103</b>

<b>Chapter 5 Bibliography.....</b>	<b>111</b>
------------------------------------	------------

## List of Tables

### Chapter 1

<b>Table 1.1</b> Sports Medicine Australia extreme heat policy environmental threshold guidelines (Adapted from Chalmers and Jay (2018))	7
<b>Table 1.2</b> Summary of environmental conditions reported during studies of running, cycling and swimming in training and competition.	10
<b>Table 1.3</b> Changes in body temperature of swimmers undertaking exercise at different water temperature (Adapted from Macaluso et al (2013))	19
<b>Table 1.4</b> The effect of hot ambient temperature (HOT; $\geq 30^{\circ}\text{C}$ ) compared to a temperate control (CON; $\leq 25^{\circ}\text{C}$ ) on endurance cycling performance for trained cyclists.	29

### Chapter 2

<b>Table 2.1</b> Participant characteristics	49
<b>Table 2.2</b> Swim training session prescription including high intensity interval training for elite swimmers (n = 9).	52
<b>Table 2.3</b> Swim training session prescription including sprint training repetitions for sub-elite swimmers (n = 10).	53
<b>Table 2.4</b> Criteria for area of interest assessment subsequently used to quantify skin temperature using the thermal imaging camera.	57
<b>Table 2.5</b> Mean environmental conditions during outdoor swimming training in elite swimmers during a COOL trial completed in spring and a WARM trial completed in summer, and in sub-elite swimmers during a HOT trial completed in summer compared to a COLD trial completed in winter.	61
<b>Table 2.6</b> Thermal comfort during outdoor high intensity training sessions for elite swimmers in COOL ( $T_a = 15.5^{\circ}\text{C}$ , WBGT = $14.7^{\circ}\text{C}$ ) and WARM ( $T_a = 23.4^{\circ}\text{C}$ , WBGT $23.0^{\circ}\text{C}$ )	

conditions and sprint training sessions for sub-elite swimmers in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions. \_\_\_\_\_ 71

**Table 2.7** Urine specific gravity, fluid consumption, whole body sweat loss and sweat rate of elite swimmers during outdoor high intensity training sessions in COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions and sub elite swimmers sprint training sessions in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions. \_\_\_\_\_ 73

### Chapter 3

**Table 3.1** Participant characteristics \_\_\_\_\_ 83

**Table 3.2** Waking urine specific gravity, fluid consumption, fluid loss, body weight change and sweat rate of endurance trained triathletes ( $n = 11$ ) in hot and humid conditions during ~60 min cycling bout (63% peak power output) followed by a time trial ( $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$ ) after consuming either a  $20 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) or placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). \_\_\_\_\_ 98

# List of Figures

## Chapter 1

<b>Figure 1.1</b> Mean temperature change in Australia from 1970 to 2019 (Australian Bureau of Meteorology, 2020).	5
<b>Figure 1.2</b> Median daily wet-bulb globe temperature (WBGT) in the previous three Summer Olympics and the predicted values for the Tokyo 2020 Summer Olympics.	8
<b>Figure 1.3</b> Effect of divergent environmental conditions on cardiovascular, neuromuscular, and metabolic function during high intensity exercise in humans.	15
<b>Figure 1.4</b> Physiological determinants of modality specific variation in thermal strain and performance effect of hot and humid conditions between running and cycling for trained athletes.	23
<b>Figure 1.5</b> The effect of environmental factors on sprint and endurance exercise performance of terrestrial (running and cycling) and aquatic (swimming) sports in training and competition.	25
<b>Figure 1.6</b> Comparison of optimal performance band for terrestrial (running and cycling) and aquatic (swimming) sports.	34
<b>Figure 1.7</b> Summary of the physiological, perceptual and performance effects of common pre-cooling (ice slushie/slurry, cold water immersion, ice vest/cooling packs) and per-cooling (ice slushie/slurry, ice vest/cooling packs, facial water spray, menthol ingestion/spray, acetaminophen ingestion) methods on endurance exercise in hot ( $T_a \geq 30^\circ\text{C}$ ) conditions.	39



## Chapter 2

**Figure 2.1** Representative thermal images for analysis of surface temperature of the (A) anterior surface, (B) the lateral surface and (C) the posterior surface for each participant.

57

**Figure 2.2** Mean 100 m repetition time for elite swimmers during outdoor high intensity training sessions in COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions. **Error! Bookmark not defined.**

**Figure 2.4** Core temperature during outdoor swim training for (A) elite swimmers undertaking a high intensity interval training session in COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions and (B) sub-elite swimmers undertaking a sprint training session in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions.

65

**Figure 2.5** Mean skin temperature during outdoor swim training for (A) elite swimmers undertaking a high intensity training session in COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions and (B) sub-elite swimmers during outdoor sprint training sessions in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions.

67

**Figure 2.6** Thermal sensation during outdoor high intensity training sessions for (A) elite swimmers in COOL ( $T_a$  = 15.5°C, WBGT = 14.7°C) and WARM ( $T_a$  = 23.4°C, WBGT = 23.0°C) conditions and sprint training sessions for (B) sub-elite swimmers in COLD ( $T_a$  = 11.8°C, WBGT = 10.3°C) and HOT ( $T_a$  = 26.3°C, WBGT = 27.0°C) conditions.

69

## Chapter 3

**Figure 3.1** Overview of an experimental trial (n=11 participants) showing the steady state cycling and time trial, and timeline of dependent variable data collection to determine physiological and perceptual responses. \_\_\_\_\_ 86

**Figure 3.2** Time to completion of a  $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  time trial in hot and humid conditions undertaken by endurance trained triathletes (n = 11) after consuming a  $20 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) or placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). \_\_\_\_\_ 92

**Figure 3.3** Time to completion for each 10% of work during a cycling time trial ( $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$ ) in hot and humid conditions undertaken by endurance trained triathletes (n = 11) after consuming  $20 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) and placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). \_\_\_\_\_ 93

**Figure 3.4** Core temperature (A), skin temperature (B) and heart rate (C) responses in hot and humid conditions of endurance trained triathletes (A: n = 11, B: n = 9, C: n = 10) during ~60 min steady state cycling (63% peak power output) and a cycling time-trial ( $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$ ) after consuming  $20 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) and placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). \_\_\_\_\_ 95

**Figure 3.5** Rating of perceived exertion (A), thermal sensation (B) and thermal comfort (C) of endurance trained triathletes (A: n = 10, B and C: n = 7) in hot and humid conditions during ~60 min steady state cycling (63% peak power output) and  $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  time trial after consuming a  $20 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) or placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). \_\_\_\_\_ 97

## List of Equations

### Chapter 1

Equation 1.1 Net heat exchange in humans \_\_\_\_\_ 3

Equation 1.2 Wet bulb globe temperature (WBGT) \_\_\_\_\_ 6

### Chapter 2

Equation 2.1 Mean Skin Temperature (Roberts, Wenger, Stolwijk & Nadel, 1977) \_\_\_\_\_ 56

Equation 2.2 Whole Body Sweat Rate \_\_\_\_\_ 58

Equation 2.3 Whole Body Sweat Loss \_\_\_\_\_ 58

### Chapter 3

Equation 3.1 Whole Body Sweat Rate \_\_\_\_\_ 90

Equation 3.2 Whole Body Sweat Loss \_\_\_\_\_ 90

## Abbreviations

$\Delta$  – change or difference

ACT – acetaminophen, paracetamol

AH – absolute humidity

AOI – area of interest, for thermal imaging analysis

ANOVA – analysis of variance

AU - arbitrary units

BM – body mass

BSA – body surface area

CHO – carbohydrate

CNS – central nervous system

CO<sub>2</sub> – carbon dioxide

CON – control group

C – Celsius

DEXA – dual energy x-ray absorptiometry

d – day

*d* – Cohen’s standardised effect size

END – endurance swimmer group

FINA – Fédération Internationale de Natation

g – grams

GXT – graded exercise test

H<sub>2</sub>O – water

Hz - hertz

h – hours

IAAF – International Association of Athletics Federations

IM – individual medley order

kg – kilogram

km - kilometres

kJ – kilojoule

L - litre

L·h<sup>-1</sup> – litres per hour

L·min<sup>-1</sup> – litres per minute

min – minutes

mL – millilitre

N/A – not applicable

O<sub>2</sub> - oxygen

PLA – placebo condition

PPO – peak power output

RH – relative humidity

RPE – rating of perceived exertion

s – seconds

SMA – Sports Medicine Australia

SPR – sprint swimmer group

TC – thermal comfort

TS – thermal sensation

$T_a$  – ambient temperature

$T_c$  – core temperature

$T_{sk}$  – mean skin temperature

$T_{surface}$  – surface temperature

TT – time trial

TTE – time to exhaustion trial

$T_w$  – water temperature

<sup>TM</sup> – trademark

UCI – Union Cycliste Internationale

USA – United States of America

$\dot{V}O_2$  – volume of oxygen uptake

$\dot{V}O_{2max}$  – maximum volume of oxygen uptake

WBGT – wet bulb globe temperature

WBSL – whole body sweat loss

WBSR – whole body sweat rate

wk – week

W – Watts

y - years

---

# **Chapter 1**

## Literature Review

---



## **1.1 Overview: Athletic Performance and Thermoregulation**

Progressive overload is a key principle of training programs that promote adaptation during preparation for peak performance in athletic competition (Soligard et al., 2016). The environmental conditions in which exercise is undertaken can significantly impact the work performed during a training session and the magnitude of the training stimulus (Racinais et al., 2015). Optimal environmental conditions are rarely experienced during daily high intensity training bouts undertaken by elite athletes (Galloway & Maughan, 1997; Guy, Deakin, Edwards, Miller, & Pyne, 2015). As such, the environmental conditions and their effects on physiological responses to exercise can be a significant barrier to optimizing the quality of training yet athletes must train and/or compete in varied environmental conditions dictated by seasonal climates and geographical location. Moreover, sporting events are routinely scheduled in sub-tropical locations with hot and/or humid conditions such as the Tokyo 2020 Olympic Games and Doha 2022 FIFA World Cup. Therefore, understanding the physiological and performance effects of typical training and competition environmental conditions is important to maximize an athlete's capabilities. Further, exploring the use of novel ergogenic aids for events undertaken in extreme environmental conditions may be paramount to minimise the negative effects of environmental conditions on performance.

Contraction of skeletal muscle and mechanical efficiency, defined as the percentage of energy used to complete work during an activity, underpins training and competition. Running and cycling mechanical efficiency is typically 20-25% (Cheuvront & Haymes, 2001, Whipp & Wasserman, 1972) whilst elite swimmers have been reported to have a mechanical efficiency of ~23% during freestyle swimming (Zamparo, Cortesi, & Gatta, 2020). Therefore, ~75% of the energy produced during running, cycling, and swimming is not used for locomotion, rather is converted into heat energy. This phenomenon, termed metabolic heat production, can occur

at rest and during exercise, and this heat is dispersed into the surrounding tissue. Deviation in internal temperature is detected via afferent signals from thermoreceptors which are also activated when environmental conditions generate a change in skin temperature (Filingeri, 2016). Afferent thermoregulatory feedback from the core and skin is integrated at the hypothalamus and a variety of autonomic physiological and behavioural regulation ensues to avoid extreme deviations from the homeostatic core temperature set-point ( $\sim 37^{\circ}\text{C}$ ) and mitigate dysregulation of metabolic function (Cheung, 2010; Racinais et al., 2015).

Heat is transferred from the body to the environment via heat exchange at the skin through radiation, convection, conduction or evaporation. Accordingly, a primary autonomic response to deviations in body temperature to increase or decrease heat exchange is via systemic changes of cutaneous blood flow. The net heat exchange between the body and the external environment can be calculated using the following equation;

$$M - W = E + R + C + K + S \quad \text{Equation 1.1}$$

where the metabolic rate (M) minus the amount of mechanical work (W) (metabolic heat production) is equal to the total amount of evaporation (E), radiation (R), convection (C), conduction (K) and storage (S) by the body (Parsons, 2014). When metabolic heat production is greater than the transfer of heat to the external environment positive heat exchange (heat storage) occurs. Conversely, when heat transfer exceeds metabolic heat production, there is a negative heat exchange (heat loss).

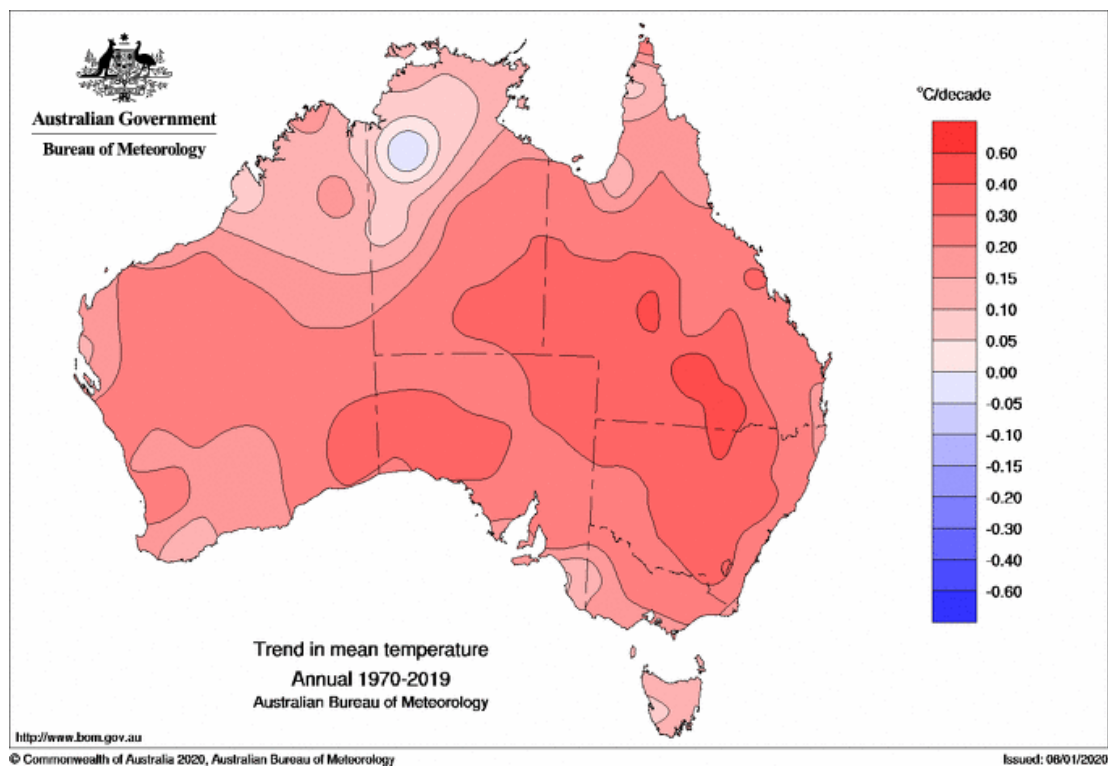
Deviations of core temperature and the associated autonomic response has a variety of effects on athlete physiology and performance. For land-based power and sprint events elevated muscle temperature increases the efficiency of excitation-contraction coupling for enhanced performance that may be achieved without significant changes in core temperature, even in hot environmental conditions (Girard, Brocherie, & Bishop, 2015; Guy et al., 2015). However, for

land-based endurance events performed in the heat, the prolonged increase in metabolic heat production and associated cardiovascular strain can limit endurance exercise performance (Trangmar & González-Alonso, 2019).

Evaporation is the predominant heat transfer mechanism during land-based exercise modalities (Sawka, Cheuvront, & Kenefick, 2012). Therefore, relatively low ambient temperatures are optimal for athletic performance in endurance running (Ely, Cheuvront, Roberts, & Montain, 2007) and cycling (Galloway & Maughan, 1997). Conversely, for swimmers who train and compete in water, the effect of the environment on thermoregulation and performance is not well-defined. Convection and conduction are the predominant heat transfer mechanisms in water and it would seem reasonable to suggest that excessive heat loss rather than heat gain is likely to influence swimming training and competition performance. However, common measures of heat balance such as core and skin temperature are rarely quantified in elite swimmers *in situ* during training. Understanding the impact of thermoregulation on athletic performance across common exercise modalities such as running, cycling and swimming is important for elite athletes training and competing under thermal stress. Therefore, this chapter will highlight the environmental challenges for elite athletes during training and competition and review the effect of thermoregulatory stress on human physiology and performance when running, cycling, and swimming. It will also provide an overview of ergogenic aids purported to induce beneficial effects for endurance performance in hot and humid conditions.

## 1.2 Current and Future Environmental Challenges for Athletes

Climate change has increased the likelihood of heatwaves and the number of “hot days” globally (Keywood, Emmerson, & Hibberd, 2016). For example, mean land surface temperature has increased across most of the Australian continent over the past 60 years and this warming pattern is expected to continue (Figure 1.1). As a result, it is likely that modern-day athletes will be exposed to more varied and hotter climatic conditions in their daily training and competition environment compared to previous generations.



**Figure 1.1** Mean temperature change in Australia from 1970 to 2019 (Commonwealth of Australia 2021, Bureau of Meteorology). Red colouration shows mean temperature has increased and blue mean temperature has decreased. The magnitude of change is expressed in °C per decade with darker shade indicating greater magnitude of change. [Map](#) licensed under the Creative Commons (CC) Attribution 3.0 [licence](#).

Historically, ambient temperature has been the most common metric to assess the thermal stress of the environment. Hot environmental conditions have been defined previously in thermal physiology literature as those where ambient temperature is  $\geq 30^{\circ}\text{C}$  (Junge, Jørgensen, Flouris, & Nybo, 2016) and cold conditions where ambient temperature is  $\leq 15^{\circ}\text{C}$  (Racinais & Oksa, 2010). However, other environmental factors such as relative humidity and solar radiation as well as ambient temperature impact thermal stress and athletic performance (Galloway & Maughan, 1997; Maughan, Otani, & Watson, 2012; Otani, Kaya, Tamaki, Watson, & Maughan, 2016). Therefore, the need to quantify the thermal stress of a given environment led to the development of integrated metrics that account for the relative contributions of each environmental component. The wet bulb globe temperature (WBGT) is widely used as a thermal stress index as it integrates ambient temperature, humidity and solar radiation into a single metric using the following equation:

$$\begin{aligned} \text{Wet Bulb Globe Temperature (WBGT)} = & 0.1 \times (\text{Dry Bulb Temperature}) \quad \text{Equation 1.2} \\ & + 0.2 \times (\text{Black Bulb Temperature}) + \\ & 0.7 \times (\text{Wet Bulb Temperature}) \end{aligned}$$

where dry bulb accounts for the contribution from ambient temperature, black bulb solar radiation and wet bulb humidity. WBGT  $>25^{\circ}\text{C}$  is associated with high risk of heat related physiological strain (Chalmers & Jay, 2018) whereas WBGT  $<10^{\circ}\text{C}$  represents a threshold for cold-induced physiological strain (Sawka, Leon, Montain, & Sonna, 2011).

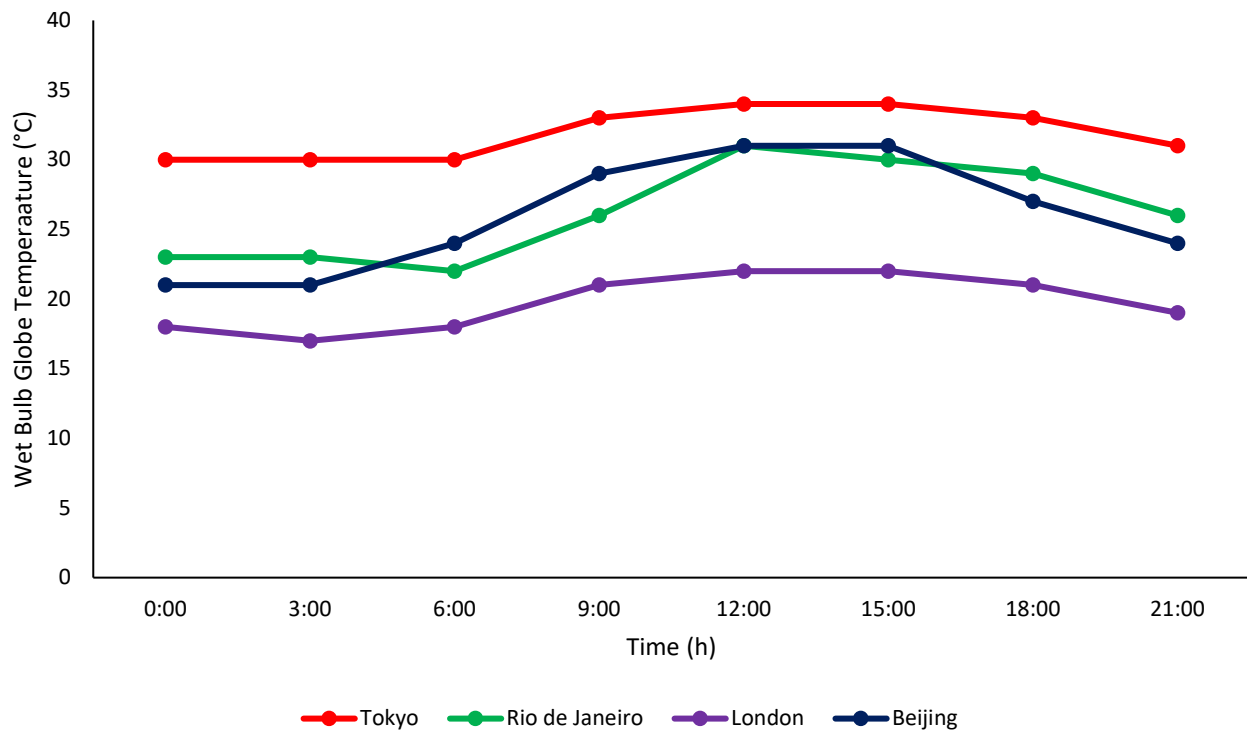
The environmental challenges for athletes is highlighted by the guidelines of Sport Medicine Australia that recommends postponing competition to a cooler part of the day or cancelling sport activities when WBGT  $> 30^{\circ}\text{C}$  (Table 1.1; Chalmers & Jay, 2018), yet WBGT is predicted to routinely exceed  $30^{\circ}\text{C}$  during the Tokyo 2020 Olympics. As such, it is expected the Tokyo games will pose the most challenging environmental conditions in recent Olympic

history (Figure 1.2 ; Kakamu, Wada, Smith, Endo, & Fukushima, 2017). Other recent and future international competitions such as the Doha 2019 IAAF World Championships and Qatar 2022 FIFA World Cup support the contention that environmental stress will be an ongoing consideration for elite athletes in training and competition.

**Table 1.1** Sports Medicine Australia extreme heat policy environmental threshold guidelines. Reprinted from Journal of Science of Medicine and Sport, 21(6), Chalmers & Jay (2018), with permission from Elsevier.

WBGT	Risk of heat illness	Recommended management for sports activities
< 20°C	Low	Heat illness can occur in distance running Caution over-motivation  Increase vigilance
21-25°C	Moderate-high	Caution over-motivation Moderate early pre-season training Take more breaks
26-29°C	High-very high	Limit intensity, take more breaks Limit duration to less than 60 min per session
≥ 30°C	Extreme	Consider postponement to a cooler part of the day or cancellation (allow swimming)

WBGT, wet bulb globe temperature.



**Figure 1.2** Median daily wet-bulb globe temperature (WBGT) in the previous three Summer Olympics and the predicted values for the Tokyo 2020 Summer Olympics. WBGT was calculated using ambient temperature and relative humidity according to the methods of the Australian Bureau of Meteorology (Adapted from Table 2. Kakamu et al (2017)).

Numerous recent recommendations and guidelines have been published to assist athletes training and competing under heat stress (Bergeron et al., 2012; Périard, Stephenson, Goosey-Tolfrey, Nikopoulos, & Migliorini, 2020; Racinais et al., 2015). Climatic conditions reported in published studies of training and competition are often reported from meteorological data rather than directly from the specific geographical site where the outdoor performance is undertaken (Table 1.2). Of the data that has been published in an applied setting, ambient temperature is most commonly reported in isolation, despite the established effect of humidity and solar radiation on thermoregulation and exercise capacity. Nonetheless, data shows that both training and competition in elite runners, cyclists and swimmers is undertaken in thermal conditions classified as high to extreme risk by SMA guidelines (Table 1.2; Ely, Cheuvront,

Roberts, et al., 2007; Guy et al., 2015; Hue et al., 2013; Hue, Monjo, & Riera, 2015; Racinais et al., 2019). For example, marathons can occur in a range of conditions from high to low heat illness risk dependent on geographical location (El Helou et al., 2012; Ely, Cheuvront, Roberts, et al., 2007). Reduction in performance and heat illness incidence during marathons also often occur in conditions much cooler than most laboratory studies (Ely, Cheuvront, Roberts, et al., 2007). Clearly, athletes train and compete in thermally challenging conditions which are expected to become more extreme and location, time of day, exercise mode, and intensity and duration are amongst a variety of factors that will determine the physiological strain experienced by athletes in training and competition. In particular, there is a paucity of data on thermoregulation during swimming, and the potential effects of the daily training environment on swimming may be understated. Moreover, the extent to which laboratory studies are translatable to training and competition contexts is unclear.



**Table 1.2** Summary of environmental conditions reported during studies of running, cycling and swimming in training and competition. Data are presented as mean  $\pm$  standard deviation or range (minimum-maximum). N/A, not applicable to the sport; ~, not reported.

Reference	Event	Water Temperature (°C)	Ambient Temperature (°C)	Relative Humidity (%)	Solar Radiation (W·m <sup>-2</sup> )	WBGT (°C)	SMA Heat Illness Risk
El Helou et al. (2012)	Marathon (Berlin, Boston, Chicago, London, New York, Paris)	N/A	1.7 - 25.2	~	~	~	~
Ely, Cheuvront, Roberts, et al. (2007)	Marathon (USA, n = 6)	N/A	5 - 28	~	~	6 - 25	Low to High-Very High
Guy et al (2015)	IAAF World Athletics Championships (1999-2011)	N/A	Pooled Mean: 24.5 Temperate: 18.5 $\pm$ 3.2 Hot: 30.0 $\pm$ 4.3	~	~	~	~

Reference	Event	Water Temperature (°C)	Ambient Temperature (°C)	Relative Humidity (%)	Solar Radiation (W·m <sup>-2</sup> )	WBGT (°C)	SMA Heat Illness Risk
Racinais et al. (2021)	IAAF World Athletics Championships 2019 (Doha)	N/A	Marathon (Women):	Marathon (Women):	~	Marathon (Women):	Moderate – Very High
			32.0 ± 0.7	77.9 ± 2.3		29.6 ± 0.3	
			Marathon (Men):	Marathon (Men):		Marathon (Men):	
			29.3 ± 0.5	46.3 ± 1.0		23.5 ± 0.4	
Racinais et al (2019)	UCI 2018 World Cycling Championships (Doha)	N/A	36.9 ± 2.8	24.6 ± 15.6	~	27.1 ± 2.4	High – Very High
Hue, Antoine-Jonville, and Sara (2007)	Junior National Swimmers Training (Guadeloupe, French West Indies; Font-Romeu, France; Montpellier, France)	27.1 - 30.0	0 - 30	~	~	~	~

Reference	Event	Water Temperature (°C)	Ambient Temperature (°C)	Relative Humidity (%)	Solar Radiation (W·m <sup>-2</sup> )	WBGT (°C)	SMA Heat Illness Risk
Hue et al. (2015)	Elite Open Water Swimming; Training and Competition (Ocean)	28.1 - 28.8	~	~	~	28.9 - 30.0	High to Extreme
Hue et al. (2013)	Elite Long-Distance Swimming; Training (Pool)	29.5 ± 0.5	~	73 ± 10	~	27.5 ± 2.3	High-Very High

## 1.3 Effect of Thermoregulatory Stress on Human Physiology

### 1.3.1 Hot Conditions

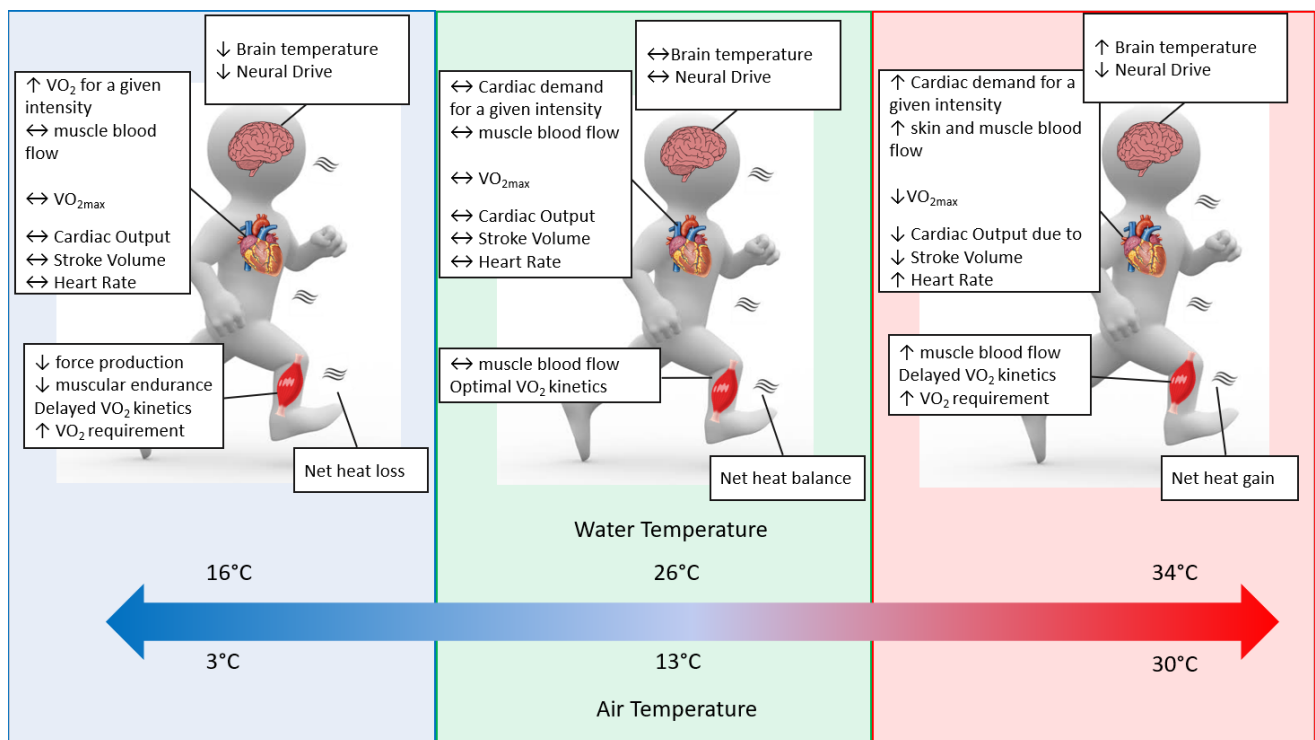
During exercise in hot and humid conditions, the body has a range of physiological responses to attenuate disruption to homeostasis by promoting heat loss and maintaining blood flow to skeletal muscle for exercise. During light to moderate intensity exercise in normothermic conditions cardiac output increases at the onset of exercise largely due to increased oxygen demand of contracting skeletal muscle concomitant with a modest increase in skin blood flow for heat exchange to the environment (González-Alonso, Crandall, & Johnson, 2008). Prolonged exercise bouts in hot conditions results in an increase in heart rate to maintain cardiac output (Chou, Akins, Crawford, Allen, & Coyle, 2019; Trinity, Pahnke, Lee, & Coyle, 2010) due to competing skin and muscle blood flow demands and decreases in plasma volume (Trangmar & González-Alonso, 2019). Consequently, the competing demands between the need for increased skin evaporation and maintaining oxygen delivery for muscle contraction during endurance exercise in hot conditions typically results in greater physiological strain and reduced exercise capacity (González-Alonso & Calbet, 2003). Therefore, cardiac output increases at a lower relative mechanical work during exercise in hot compared to normothermic conditions (Arngrímsson, Stewart, Borrani, Skinner, & Cureton, 2003; Chou, Allen, Hahn, Leary, & Coyle, 2018). Core temperature and skin temperature first rise then plateau once allostasis is established, representative of a physiological state known as *compensable heat stress* which occurs alongside thermal strain during low to moderate-intensity steady state exercise in environmental conditions where humidity and solar radiation are low-moderate (Sawka et al., 2012).

During high intensity endurance exercise in hot conditions, where the evaporative requirement for heat balance exceeds the maximal evaporative capacity of the environment, cardiac output can quickly plateau, then reduce due to a reduction in ventricular filling and stroke volume

caused the combination of thermal strain and associated high sweat rates, and the ensuing exercise induced dehydration (Trangmar & González-Alonso, 2019). This in turn reduces the efficiency of evaporative cooling, leading to greater skin temperature and increased heat storage, elevating core temperature as heat stress becomes uncompensable (González-Alonso et al., 2008; Sawka et al., 2012). Extended periods where the evaporative requirement of the environment exceeds the evaporation capacity of the body can cause uncontrolled heat storage (Cramer & Jay, 2016; Sawka et al., 2012). Initial studies suggested that high core temperatures ( $> 40^{\circ}\text{C}$ ) were predictive for the onset of exertional heat illness and exercise cessation in athletes (Brotherhood, 2008, González-Alonso et al., 2008). However, more recent data shows highly trained cyclists can tolerate core temperatures up to  $\sim 41.5^{\circ}\text{C}$  without symptoms of exertional heat illness (Racinais et al., 2019). Therefore, the onset of heat illness appears to be regulated by several factors that may include genetic predisposition and endotoxemia independent of high core temperature and heat balance (Laitano, Leon, Roberts, & Sawka, 2019). The exercise intensity at which maximal oxygen uptake occurs decreases with thermal strain in high ambient temperatures and humidity, reducing an athlete's maximal work capacity (González-Alonso & Calbet, 2003; González-Alonso et al., 1999; Nybo, Jensen, Nielsen, & González-Alonso, 2001). Additionally, thermal strain may also result in a reduction in neural drive and impaired neuromuscular coordination (Nybo, Secher, & Nielsen, 2002) which contributes to lower power output during endurance exercise in hot, humid conditions (Nybo & Nielsen, 2001; Todd, Butler, Taylor, & Gandevia, 2005).

Core and skin temperature are the primary indicators of the amount of heat storage in the body (Cramer & Jay, 2016) with a decrease in the gradient between core and skin temperature associated with reductions in aerobic capacity in hot conditions (Cuddy, Hailes, & Ruby, 2014). Core temperature can be measured using oesophageal, rectal or gastrointestinal thermistors (Ganio et al., 2009) and is closely associated with intramuscular temperature which influences

the efficiency of the excitation-contraction coupling reaction (Todd, Gordon, Groeller, & Taylor, 2014). Intramuscular temperature that is too low ( $<32^{\circ}\text{C}$ ) or too high ( $>38^{\circ}\text{C}$ ) delays  $\dot{V}\text{O}_2$  kinetics at the muscle (González-Alonso & Calbet, 2003; Sargeant, 1987) and represents the upper and lower limits for optimal muscle contraction and sprint exercise performance. Muscle temperature is important for the performance of short duration, high intensity exercise bouts such as sprint running, cycling or swimming. Therefore, passive and active heating of skeletal muscle above basal temperatures may improve sprint performance (Girard et al., 2015; Yaicharoen, Wallman, Bishop, & Morton, 2012). However, the relationship between tissue temperature and endurance exercise performance is more complex and primarily dependent on exercise duration, intensity, modality, and environmental conditions (Figure 1.3).



**Figure 1.3** Effect of divergent environmental conditions on cardiovascular, neuromuscular, and metabolic function during high intensity exercise in humans. Indicative water and ambient temperature of cold (blue), temperate (green) and hot (red) environmental conditions are displayed.

### 1.3.2 Cold Conditions

Thermoregulation is equally important in cold, as it is in hot, conditions due to the effect of cold environmental conditions on muscle contractility (Wakabayashi et al., 2018), neuromuscular efficiency (Racinais & Oksa, 2010) and exercise performance (Nimmo, 2004). Anthropometric factors such as body fat percentage can influence individual variation in thermoregulatory responses to cold conditions (Bradford, 2018; Nimmo, 2004), but there are also other common physiological responses to cold conditions. Specifically, when skin temperature is reduced skin thermoreceptors promote peripheral vasoconstriction and shivering thermogenesis. In addition, behavioural responses may become evident in an attempt to remain in a thermoneutral state such as reducing exposure of body surface area through changes in posture (e.g. folding arms, crouching etc.) or clothing (Filingeri, 2016; Nimmo, 2004).

Peripheral vasoconstriction reduces skin blood flow which in turn decreases the convective transfer of heat from warm skin to the cold environment (Cheung, 2010). Shivering thermogenesis increases metabolic heat production via involuntary muscle contractions raising the energetic cost at rest and during activity to augment maintenance of core temperature within homeostatic limits (Cheung, 2010). Maintaining muscle temperature through shivering thermogenesis sustains a relative efficiency of the excitation-contraction reaction in cold conditions when behavioural responses are insufficient (Costello, Culligan, Selfe, & Donnelly, 2012). However, muscle oxygen kinetics and exercise efficiency may be reduced in the cold (Wakabayashi et al., 2018), while relative  $\dot{V}O_2$  increases at the same absolute sub-maximal exercise intensity in cold conditions due to the added energetic cost of shivering thermogenesis (McArdle, Magel, Lesmes, & Pechar, 1976). Reduced neuromuscular efficiency also reduces exercise performance due to impaired coordination and agonist-antagonist neural coactivation (Racinais & Oksa, 2010).

Cold conditions are particularly challenging for athletes training and competing in aquatic sports because large amounts of heat loss can occur due to the high heat capacity of water and low insulation of swimsuits (Nadel, 1984). In addition, trained swimmers typically have low subcutaneous fat deposits and are likely to have a propensity to cool faster than the general population (Saycell, Lomax, Massey & Tipton, 2018). Since the limited insight into thermal physiology during swimming has focused on recreationally active rather than elite athletes the current literature may have limited translational value to athletes (Table 1.3). Swimming in water temperatures lower than resting skin temperature causes large reductions in skin temperature and muscle temperature due to the magnitude of heat transfer caused by conduction and convection in water (Costill, Cahill, & Eddy, 1967; Fujishima et al., 2001; Galbo et al., 1979; Holmér & Bergh, 1974). Thus, water temperature and exercise intensity are the primary determinants of heat storage whilst exercising in aquatic environments. If water temperature is temperate and exercise intensity is near maximal, metabolic heat may maintain core temperature despite low skin temperature (Costill et al., 1967; Nadel, Holmer, Bergh, Astrand, & Stolwijk, 1974). However, during slow sub-maximal swimming bouts (velocity  $\leq 0.75\text{m}\cdot\text{s}^{-1}$ ) in water temperatures colder than  $27^{\circ}\text{C}$ , metabolic heat may not maintain core and skin temperature and exercise economy reduces with increased energetic cost attributed to shivering thermogenesis (Fujishima et al., 2001; Holmér & Bergh, 1974; Nadel et al., 1974). Increases in velocity seem to have little influence on the heat transfer coefficient whilst swimming ( $580\text{ W}\cdot\text{m}^{-2}\cdot^{\circ}\text{C}^{-1}$ ) therefore body surface area and difference between skin and water temperature have the largest effects on heat loss (Nadel et al., 1974). Since elite swimmers typically train and compete indoors in temperature-controlled pools, the risk of excess heat storage during swimming is reduced compared to elite athletes training on land where effective heat dissipation can be limited. Nevertheless, a substantial number of swimmers train outdoors throughout the year where the seasonal variation in ambient and water temperature may have



an influence on physiology and performance. Little is known about the effect of cold ambient conditions on the physiology of swimmers, particularly elite performers. Consequently, given the potential for cold conditions during early-morning outdoor training in winter months, there is a need for further work to determine the effect of environmental conditions on physiology during swimming.

**Table 1.3** Changes in body temperature of swimmers undertaking exercise at different water temperature (Adapted from Macaluso et al (2013)).

References	Time/Distance	Intensity	Swimming Ability	Water Temperature (°C)	Measurement	Temperature Effect (°C)	
Costill et al. (1967)	20 min	Work at 150 bpm estimated by submaximal swimming test	n = 8 “proficient swimmers” in “excellent physical condition”	17	Rectal	↔	
				27	Rectal	↑	+ 0.5
				33	Rectal	↑	+ 0.8
				17	Skin	↓	- 14.0
				27	Skin	↓	- 5.0
				33	Skin	↑	+ 1.0
Nadel et al. (1974)	20 min	40% VO <sub>2max</sub>	n = 3 “excellent swimmers”	18-26	Rectal	↓	- 0.5
		0.50 m·s <sup>-1</sup>		33	Rectal	↑	+ 1.0
		70% VO <sub>2max</sub>	n = 3 “excellent swimmers”	18	Rectal	↓	- 0.5
		0.75 m·s <sup>-1</sup>		26	Rectal	↑	+ 0.7
				34	Rectal	↑	+ 1.5

References	Time/Distance	Intensity	Swimming Ability	Water Temperature (°C)	Measurement	Temperature Effect (°C)	
Holmér and Bergh (1974)	20 min	~50% $\text{VO}_{2\text{max}}$	Swimming $\text{VO}_{2\text{max}}$ = $3.72 \pm 0.32$ $\text{L} \cdot \text{min}^{-1}$ (n = 2 untrained, n = 3 trained)	18	Oesophageal	↔	
				26	Oesophageal	↑	+ 0.5
				34	Oesophageal	↑	+ 1.0
	5-8 min	Graded swimming test (Maximal)  $0.5\text{-}1.2 \text{ m} \cdot \text{s}^{-1}$	Swimming $\text{VO}_{2\text{max}}$ = $3.72 \pm 0.32$ $\text{L} \cdot \text{min}^{-1}$	18	Oesophageal	↔	
				26	Oesophageal	↑	+ 0.5
				34	Oesophageal	↑	+ 1.0
	60 min	~65% $\text{VO}_{2\text{max}}$	Swimming $\text{VO}_{2\text{max}}$ 3.74 (2.65-4.27) $\text{L} \cdot \text{min}^{-1}$	21	Rectal	↓	- 0.8
				27	Rectal	↑	+ 0.7
				33	Rectal	↑	+ 1.3

References	Time/Distance	Intensity	Swimming Ability	Water Temperature (°C)	Measurement	Temperature Effect (°C)	
Fujishima et al. (2001)	120 min	~50% VO <sub>2max</sub>	Swimming VO <sub>2max</sub> = 3.63 ± 0.23 L·min <sup>-1</sup>	23-28	Rectal	↓	- 1.0
				33	Rectal	↔	
				23	Skin	↓	- 5.0
				28	Skin	↓	- 3.5
				33	Skin	↑	+ 1.5
Macaluso et al. (2011)	5km pool swim	Time Trial (Maximal)	“Competitive Masters Swimmers”	23	Rectal	↔	
				27	Rectal	↑	+ 1.0
				32	Rectal	↑	+ 2.0

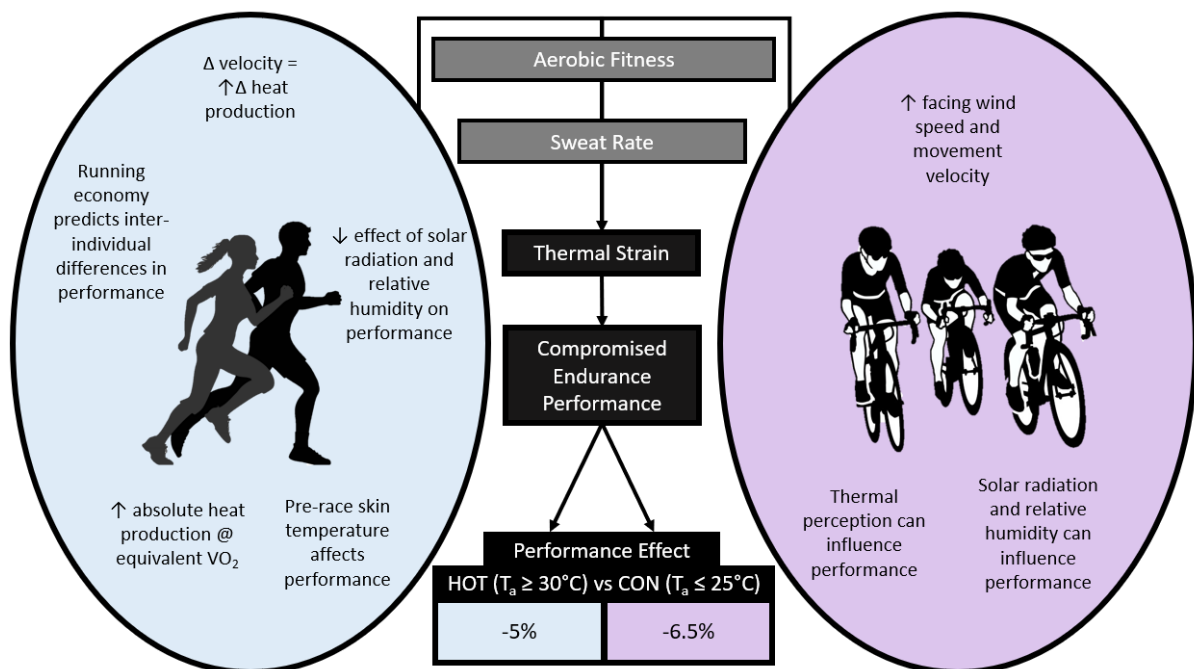
## **1.4 Effect of Thermoregulatory Stress on Human Performance**

Thermoregulatory stress exacerbates physiological strain and limits human work capacity during exercise which alters human performance during training and competition. Physiological and performance responses during running, cycling and swimming competition can vary, even when ambient temperature, humidity and/or solar radiation are comparable, due to differing metabolic demands, heat transfer and duration for each exercise modality.

### **1.4.1 Running**

Running and cycling occur in a terrestrial environment where the factors which influence performance include ambient temperature, humidity, solar radiation and wind speed (Cheung, 2010; Racinais et al., 2015). Runners exhibit higher core temperatures than cyclists during comparable endurance exercise due to increased heat storage (Nassis & Geladas, 2002). Additionally, increasing running velocity causes a larger rise in total work compared to an equivalent increase in cycling pace (Bijker, de Groot, & Hollander, 2001). Competitive runners who change pace regularly when competing could experience large perturbations in metabolic heat production depending on their pacing strategies. Also, since runners experience lower wind speed relative to cyclists, heat exchange is reduced given wind speed increases heat transfer independent of sweat rate (Saunders, Dugas, Tucker, Lambert, & Noakes, 2005). Despite runners and cyclists exhibiting similar sweat rates (Garth & Burke, 2013), runners experience higher absolute metabolic heat loads and are more inefficient in heat dissipation compared to cyclists (Nassis & Geladas, 2002). Therefore, the performance of endurance runners may be compromised to a larger extent in hot conditions than endurance cyclists due to increased heat storage during equivalent amounts of relative work. Surprisingly, little laboratory or field data on the performance of runners in hot conditions compared to a temperate control exists. Of the limited studies available, they seem to suggest that performance decrements of ~5% on running performance may be expected in hot conditions (Ely et al.,

2009; Hanson et al., 2018; Junge, Jørgensen, Flouris, & Nybo, 2016). Moreover, when employing facing wind-speed replicating competition, Chan, Wong, and Chen (2008) report similar 40 km cycling performance but impaired 10 km running performance (~16%) during a simulated Olympic distance triathlon in high (31.2°C) compared to moderate (22°C) ambient temperature. Despite increased absolute heat storage when running compared to cycling, the performance effects observed seem equivalent in running time-trials of a comparable duration to cycling (Figure 1.4). However, performance during a running bout may be compromised in hot conditions when completed after cycling such as during a triathlon simulation.

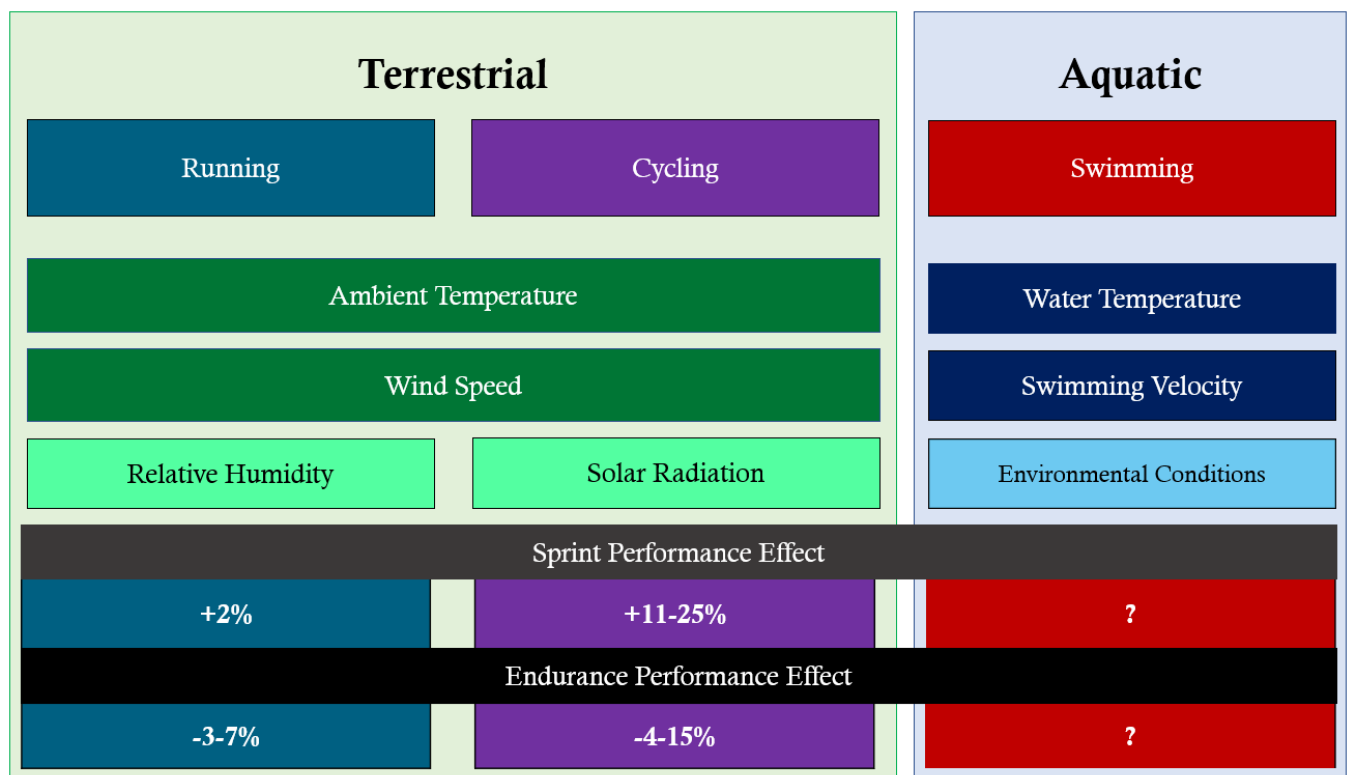


**Figure 1.4** Physiological determinants of modality specific variation in thermal strain and performance effect of hot and humid conditions between running and cycling for trained athletes. Blue shading denotes determinants and time trial performance effect for running and purple shading denotes determinants and time trial performance effect for cycling in hot ( $T_a \geq 30^\circ\text{C}$ ) compared to a control condition ( $T_a \leq 25^\circ\text{C}$ ). Grey shaded boxes describe common factors which influence performance of all athletes in the heat. Mean performance effect is displayed. The most recent evidence from field-based studies suggests that for elite athletes,

pre-race skin temperature may affect marathon performance rather than pre-race and competition core temperature (Racinais et al., 2021). Since ambient temperature largely determines skin temperature during controlled laboratory studies and simulated time trials, it may be the main determinant of endurance running performance in competition (Meade & Kenny, 2017; Périard et al., 2020). Indeed, hot conditions reduce marathon performance, with the optimal environment reported to be an ambient temperature range between  $\sim 4^{\circ}\text{C}$  and  $\sim 10^{\circ}\text{C}$  (El Helou et al., 2012).

Relative humidity and solar radiation affect exercise performance (Maughan et al., 2012; Otani et al., 2016) but empirical evidence of cause and effect of these environmental factors on human running capacity is limited (Figure 1.5). Che Muhamed, Atkins, Stannard, Mündel, and Thompson (2016) have shown an inverse relationship between relative humidity and time to exhaustion during a maximal graded running test. Performance time is also reduced during exercise to exhaustion at 70%  $\text{VO}_{2\text{max}}$  in warm humid conditions ( $T_a$   $30^{\circ}\text{C}$ , RH 71%) compared to warm dry conditions ( $T_a$   $30^{\circ}\text{C}$ , RH 24%; Che Muhamed, Yusof, Stannard, Mündel, & Thompson, 2019). There is a paucity of studies on effects of solar radiation during running and the data are limited to race conditions with low solar radiation (range  $130\text{-}523\text{ W}\cdot\text{m}^{-2}$ ,  $T_a \approx 12^{\circ}\text{C}$ ; Ely, Cheuvront, & Montain, 2007) or when integrated within WBGT during college running competition, and the relationships between performance and WBGT were variable (McCann & Adams, 1997).

In summary, running performance seems to be reduced in conditions with high ambient temperature and relative humidity, respectively. Meaningful studies on solar radiation have yet to be undertaken and efforts to predict heat stress using the WBGT index were inconclusive. More applied research which quantifies and compares the combined and individual effect of all environmental factors on running performance are needed to provide clarity on the thermal challenges experienced by runners in training and competition.



**Figure 1.5** The effect of hot ( $\geq 30^{\circ}\text{C}$ ) compared to a temperate (control [CON];  $\leq 25^{\circ}\text{C}$ ) ambient temperature on sprint and endurance exercise performance of terrestrial (running and cycling) and aquatic (swimming) sports in training and competition. Performance effect range for each exercise modality is reported (blue, running; purple, cycling; red, swimming).

#### 1.4.2 Cycling

The effects of ambient temperature, humidity and solar radiation during cycling share many common physiological responses with running. For example, like running velocity, sprint cycling peak power increases when muscle is heated via passive heating (11%) and active



metabolic heat production (25%; Girard et al., 2015). Additionally, peak power during repeat sprint cycling increases in hotter ambient temperatures when core temperature  $<38^{\circ}\text{C}$  (Girard, Bishop, & Racinais, 2013; Girard et al., 2015). However, when core temperature is elevated, the beneficial effect of ambient temperature on repeat sprint performance is attenuated (Drust, Rasmussen, Mohr, Nielsen, & Nybo, 2005), an effect associated with decreased central nervous system function (Nybo & Nielsen, 2001).

Exercise capacity in endurance cycling is reduced in hot ambient temperatures ( $\geq 30^{\circ}\text{C}$ ) compared to temperate/cold temperatures ( $\leq 25^{\circ}\text{C}$ ; Table 1.4; Febbraio et al., 1996; Galloway & Maughan, 1997; Parkin, Carey, Zhao & Febbraio, 1999). Physiological responses during cycling in hot ambient temperatures are comparable to running, including increased core and skin temperature and elevated heart rate which reduce maximal aerobic capacity (Racinais et al., 2015; Trangmar & González-Alonso, 2019). Generally, performance time during an endurance cycling bout is maximized at cool ambient temperatures ( $11^{\circ}\text{C}$ ) for moderate intensity ( $70\% \text{VO}_{2\text{max}}$ ) cycling to exhaustion due to optimal heat balance and metabolic efficiency, and a  $\sim 36\%$  increase in time to exhaustion has been reported in hot ( $T_a = 31^{\circ}\text{C}$ ) compared to temperate conditions ( $T_a = 21^{\circ}\text{C}$ ; Galloway & Maughan, 1997). During cycling time trials greater than 30 minutes duration, this impaired performance effect is between 4-14% in hot ( $T_a \geq 30^{\circ}\text{C}$ ) compared to temperate conditions ( $T_a \leq 25^{\circ}\text{C}$ ; Table 1.4; Abbiss et al., 2010; Castle, Maxwell, Allchorn, Mauger, & White, 2012; Chan et al., 2008; Faulkner et al., 2019; Maia-Lima et al., 2017; Peiffer & Abbiss, 2011; Racinais, Périard, Karlsen, & Nybo, 2015; VanHaitsma et al., 2016). Collectively, the mean effect of several studies employing 40 km time trials with  $\sim 15^{\circ}\text{C}$  temperature differentials between trial conditions appear to show a  $\sim 6\%$  decrease in performance in the heat ( $32\text{-}35^{\circ}\text{C}$ ) and poorer endurance cycling performance has also been reported in ambient temperatures  $>30^{\circ}\text{C}$  when compared to ambient temperatures

at least 9°C cooler (Table 1.4). Accordingly, decreased cycling performance in the heat may be dependent on, at least in part, the magnitude of difference in ambient temperature and the exercise duration. However, it is difficult to clearly define the negative impact on performance due to heterogeneity in experimental designs and the limited number of studies. Impaired performance in hot conditions has been purported to occur due to an anticipatory reduction in power output associated with the initial rates of heat storage during an endurance cycling bout (Tucker, Marle, Lambert, & Noakes, 2006). Since pacing during endurance cycling races is variable, the lower power outputs may occur during the middle of a race to preserve high intensity or sprint capacity to respond to tactical moves or sprint finishing efforts (Schmit, Duffield, Hausswirth, Coutts, & Le Meur, 2016; Tucker, Rauch, Harley, & Noakes, 2004).

A common methodological limitation for laboratory cycling studies is that facing wind speed is rarely equivalent to that experienced during competition despite its large effect on heat exchange and performance (Saunders et al., 2005). Convective and evaporative heat loss are increased when cycling with facing wind speed  $\geq 2.78 \text{ m}\cdot\text{s}^{-1}$  ( $10 \text{ km}\cdot\text{h}^{-1}$ ) compared to still air (Otani, Kaya, Tamaki, Watson & Maughan, 2017). Specifically, the contribution of evaporative heat loss increases in proportion to air velocity whilst convective heat loss does not increase at air velocities  $\geq 2.78 \text{ m}\cdot\text{s}^{-1}$  (Otani et al., 2017). Endurance performance in a time to exhaustion test increases proportionally with air velocity which intuitively is due to the effect of air velocity on increasing evaporative heat loss as air passes over the skin which slows the rate of increasing core (rectal) temperature (Otani et al., 2017). Competitive cycling typically far exceeds velocities  $\geq 2.78 \text{ m}\cdot\text{s}^{-1}$  therefore convective heat loss is maximised. Therefore, any performance effect associated with facing wind speed is primarily dependent on its effect on evaporative heat loss and is proportional to the horizontal vector in velocity of air over the skin (Nybo, 2010). As such, when facing wind speed is replicated, performance in a 40 km time trial is not different despite up to  $\sim 9^\circ\text{C}$  difference in mean ambient temperature (Chan et al.,

2008). This also may explain why ecologically valid time trials completed outdoors tend to be faster than those completed in the laboratory (Jobson et al., 2007). There is a dearth of data describing typical environmental conditions experienced by elite endurance cyclists in outdoor settings. Consequently, little is known about the interactions of wind speed, solar radiation and relative humidity on cycling performance other than their independent linear effects on laboratory endurance cycling capacity (Maughan et al., 2012; Otani et al., 2016; Saunders et al., 2005). Given the effect of heat stress on performance during cycling, effective strategies to mitigate excessive physiological strain and/or ergogenic aids to promote optimal performance are needed in hot conditions.

**Table 1.4** The effect of hot ambient temperature (HOT;  $\geq 30^{\circ}\text{C}$ ) compared to a temperate control (CON;  $\leq 25^{\circ}\text{C}$ ) on endurance cycling performance for trained cyclists. NR = not reported, \* average cycling speed outdoors reported as facing wind speed, TT = time trial, TTE = time to exhaustion trial.

Reference	Performance Test	HOT T <sub>a</sub> (°C)	CON T <sub>a</sub> (°C)	Relative Humidity (%)	Facing Wind Speed (m·s <sup>-1</sup> )	Performance Effect		
						Mean Difference (%)	Effect Size (Cohen's <i>d</i> )	p - value
Altareki, Drust, Atkinson, Cable, and Gregson (2009)	4 km TT	35	13	60	5.6	1.9	0.39	< 0.01
Tucker et al. (2004)	20 km TT	35	15	60	2.8	2.8	0.43	< 0.001
Maia-Lima et al. (2017)	30 km TT	35	24	68	0.5	4.0	1.48	< 0.001
VanHaitsma et al. (2016)	40 km TT	35	21	~25	NR	5.1	0.55	0.002
Périard et al. (2011b)	40 km TT	35	20	60/40	2.8	7.0	1.70	< 0.01
Peiffer and Abbiss (2011)	40 km TT	32	17	40	8.9	6.1	0.60	< 0.01
Périard, Cramer, Chapman, Caillaud, and Thompson (2011a)	40 km TT	35	20	60/40	2.8	7.5	1.67	< 0.01
Racinais et al. (2015)	43.4 km TT	36	8.2	13/30	9.6-10.9*	16.7	2.21	< 0.05

Reference	Performance Test	HOT T <sub>a</sub> (°C)	CON T <sub>a</sub> (°C)	Relative Humidity (%)	Facing Wind Speed (m·s <sup>-1</sup> )	Performance Effect		
						Mean Difference (%)	Effect Size (Cohen's <i>d</i> )	p - value
Abbiss et al. (2010)	100 km TT	33.7	10.5	44/65	~3.6	7.1	1.15	< 0.001
Périard and Racinais (2016)	750kJ TT	35	18	60/40	3.5	8.5	0.81	< 0.001
Ely, Cheuvront, Kenefick, and Sawka (2010)	15 min total work	40	21	50/25	NR	16.6	1.20	< 0.05
Tatterson, Hahn, Martini, and Febbraio (2000)	30 min total work	32	23	60	5.6	6.5	2.58	< 0.05
Castle et al. (2012)	30 min total work	31.4	21.8	43.3/65.4	NR	4.5	0.29	< 0.05
Faulkner et al. (2019)	60 min total work	35	24	~50	NR	7.3	1.32	< 0.01
Tucker et al. (2004)	RPE clamp (16) TTE	35	15	65	2.8	30.0	1.18	< 0.001

Reference	Performance Test	HOT T <sub>a</sub> (°C)	CON T <sub>a</sub> (°C)	Relative Humidity (%)	Facing Wind Speed (m·s <sup>-1</sup> )	Performance Effect		
						Mean Difference (%)	Effect Size (Cohen's <i>d</i> )	p - value
Galloway and Maughan (1997)	70% VO <sub>2</sub> TTE	31	11	70	0.7	44.8	8.21	0.001
Parkin et al. (1999)	70% VO <sub>2</sub> TTE	40	20	< 50	NR	49.2	3.60	< 0.05
Time Trial Mean (SD)		34.9 (4.8)	17.3 (1.3)	~	~	6.6 (4.4)	1.10 (0.6)	~
All Trials Mean (SD)		34.5 (5.9)	17.8 (2.6)	~	~	15.7 (19.3)	2.63 (1.9)	~

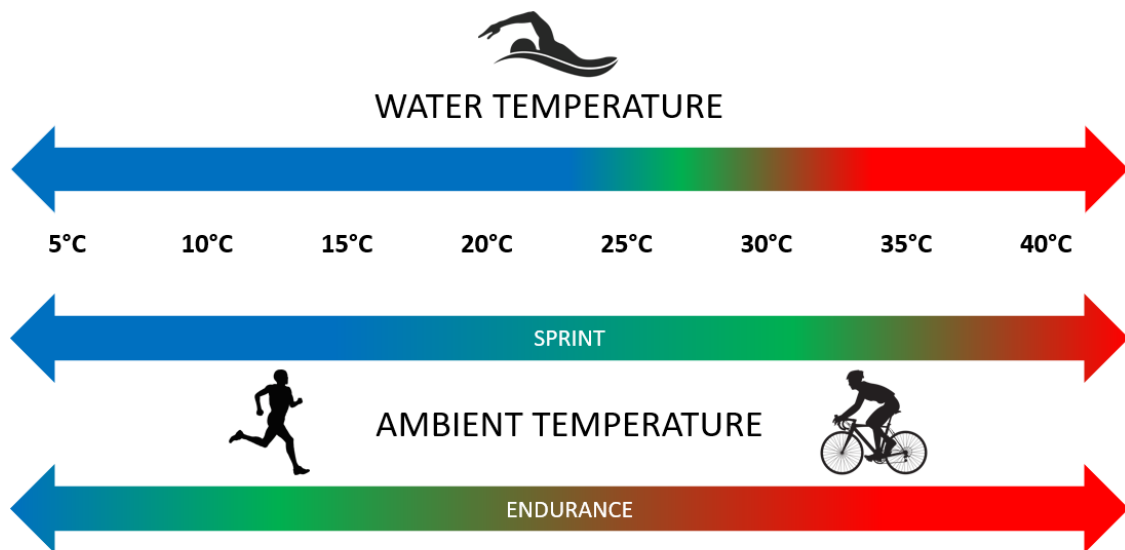
### 1.4.3 Swimming

Water temperature during swimming has a significant effect on performance (Holmér & Bergh, 1974; Nadel, 1984). Other environmental factors such as ambient temperature, relative humidity and solar radiation are not considered to influence swimming performance despite the known effects on terrestrial exercise modalities (Bergeron et al., 2012). Moreover, few studies describe the effect of environmental conditions or water temperature on the performance of highly trained swimmers during training or competition. The only study that has compared the performance of highly trained sprint swimmers in varied water temperatures indicates the optimal temperature for sprint swimming is  $\sim 29^{\circ}\text{C}$  (Figure 1.6). The authors suggest that this water temperature may permit adequate heat conductance and reduce sweat rates during high intensity swimming bouts (Robinson & Somers, 1971). However, this study defined performance as average velocity across a 60-min time trial which has little ecological validity compared to the  $\sim 25\text{-}60\text{s}$  duration efforts of typical 50 m or 100 m freestyle swim training. Bradford (2018) has suggested that  $27^{\circ}\text{C}$  is the optimal water temperature for performance during a 30 min time trial for open water swimmers (Bradford, 2018) and  $33^{\circ}\text{C}$  water temperature may be the threshold above which swimming performance may be impaired due to increased thermal strain caused by excessive heat storage (Figure 1.6; Bradford, 2018; Robinson & Somers, 1971).

Cold water also seems to limit swimming performance with water temperatures  $\leq 21^{\circ}\text{C}$  decreasing maximal swimming velocity compared to warmer water temperatures in numerous studies (Galbo et al., 1979; Holmér & Bergh, 1974; Nadel et al., 1974; Robinson & Somers, 1971; Saycell, Lomax, Massey, & Tipton, 2019). However, it is difficult to understand the relationship between the physiological responses to different water temperatures and performance outcome of swimmers because of varied experimental designs, methodologies and dependent variables. Studies show that exercise  $\dot{V}\text{O}_2$  increases during swimming in water

temperatures  $\leq 21^{\circ}\text{C}$  (Costill et al., 1967; Holmér & Bergh, 1974; McArdle et al., 1976) and the relationship between skin temperature and water temperature during swimming appears to be linear (Nadel et al., 1974) but there is insufficient data available to clearly establish a significant correlation. Additionally, little is known about the interaction between thermal sensation/comfort and swimming performance despite the capacity for cold water to rapidly induce sensations of cold, an effect that precedes decreases in core temperature (Bradford, 2018; Holmér & Bergh, 1974; Nadel, 1984; Saycell et al., 2019). Since changes in thermal sensation occur within 0-4 s due to the dynamic nature of water flow across the skin during swimming (Filingeri, 2016) there is potential for thermal sensation to negatively affect performance capacity before changes in purported physiological mechanisms that attenuate performance such as core and muscle temperature are evident (Schlader, Simmons, Stannard & Mündel, 2011a, Stevens et al., 2016). Consequently, whilst water temperature could be expected to impact short/moderate swimming performance, there are few data from which to elucidate the effects of cold/cool water temperature on physiology and performance in highly trained swimmers. Therefore, there is a clear need to determine the relationships between the physiological and perceptual responses during swimming in varied environmental and water temperatures, and their potential effect on sprint swimming performance.





**Figure 1.6** Comparison of optimal performance band for terrestrial (running and cycling) and aquatic (swimming) sports. The green zone denotes optimal water temperature for swimming performance and ambient temperature for sprint and endurance running and cycling. The blue zone in the arrow denotes temperatures at which the effect of heat loss limits exercise performance and the red zone shows temperatures at which heat storage limits exercise performance.

## 1.5 Ergogenic Aids for Exercise in the Heat

High levels of physical fitness, heat acclimatisation and acute cooling strategies are each purported to mitigate the negative effects of hot conditions on endurance exercise performance (Alhadad, Tan, & Lee, 2019). Elite athletes possess high physical fitness and commonly employ heat acclimatisation strategies before major competitive events. However, optimising cooling strategies remains a challenge for sport science practitioners and coaches/athletes alike (Racinais et al., 2020). Various cooling strategies have been investigated with the aim of developing effective and practical cooling protocols that improve endurance exercise performance (Bongers, Thijssen, Veltmeijer, Hopman, & Eijssvogels, 2015). Effective cooling

strategies in hot and humid conditions increase the core to skin temperature gradient and delay or minimise heat storage during exercise (Cuddy et al., 2014). Select strategies for endurance exercise in the heat are purported to mitigate the impaired CNS function that can occur during prolonged exercise in hot conditions (Nybo & Nielsen, 2001).

Broadly, an ergogenic aid is any strategy which assists in improving physical performance. Ergogenic aids for endurance exercise in the heat that promote heat loss mechanisms in the body before and during exercise can be categorized as nutritional, pharmaceutical and physical with varied practical and physiological benefits and limitations. Briefly, nutritional ergogenic aids typically aim to reduce the cardiovascular strain and/or neural dysfunction in hot conditions by minimizing the impact on cardiac output and peripheral vasodilation, and efferent neural activity or “neural drive” (Trangmar & González-Alonso, 2019). However, these strategies including the ingestion of caffeine, probiotics and nitrate containing supplements are scarcely used in practice due to their low efficacy for attenuating heat stress (Amano et al., 2018; Ely & Cheuvront, 2010). Physical ergogenic aids aim to reduce core temperature via the ingestion of cold substances or through cooling the skin via conduction or convection (Ross et al., 2011) through modalities such as ice slurries and slushies, and cold-water sprays or immersion. Cooling strategies are the most frequently employed physical ergogenic aid for exercise in the heat with strong evidence indicating enhanced performance when used before or during exercise in hot and humid environmental conditions (Angel Rodriguez et al., 2020; Bongers, Hopman, & Eijssvogels, 2017; Bongers et al., 2015; Ross, Abbiss, Laursen, Martin, & Burke, 2013; Stevens, Taylor, & Dascombe, 2017; Tyler, Sunderland, & Cheung, 2015). Finally, pharmaceutical ergogenic aids target cellular receptors, typically in the muscle or central nervous system, with the aim of inducing physiological responses to either reduce core temperature or attenuate thermal perception during exercise in the heat (Stevens, Mauger, Hassmén, & Taylor, 2018).

The timeline for implementing a cooling strategy is also relevant when characterizing ergogenic aids into pre-cooling or per-cooling methods. Pre-cooling involves the use of techniques to cool the body in the minutes or hours before exercise, whilst per-cooling refers to those methods undertaken after the commencement of exercise during training or competition. While it is acknowledged that the use of ergogenic aids may also be applicable to exercise performance in cool or cold environmental conditions, such strategies appear to have a strong emphasis on textiles/garments (Kerr, Trappe, Starling, & Trappe, 1998; Nimmo, 2004). Accordingly, this section will limit its focus to common pre- and per-cooling ergogenic aids used in studies of exercise in hot conditions, to synthesize the purported physiological mechanisms and benefits/limitations of common cooling modalities.

### **1.5.1 Pre-Cooling**

Pre-cooling typically includes either internal physical cooling methods such as ingestion of cold fluid or ice, or external methods that may include cooling the skin via garments or submersion in cold water (Bongers et al., 2015; Ruddock et al., 2017; Tyler et al., 2015). Employing a combination of methods (mixed methods) is also not uncommon to concurrently induce cooling of core and skin temperature (Bongers et al., 2015). Cold water immersion is a primary method for reducing core temperature and skin temperature in hot and humid conditions with ~10 min immersion in cool-to-mild water temperature (14-24°C) suggested to improve endurance exercise performance (Bongers et al., 2015). However, cold water immersion may be contraindicated in an exercise duration and intensity dependent manner due to the acute effect of cold muscle temperature on muscle contractility (Girard et al., 2015; Lloyd, Hodder, & Havenith, 2015). Specifically, high intensity short duration exercise performance (Dixon et al., 2010; Parouty et al., 2010) has been shown to decrease after lower limbs were immersed for 5-45 min in cold water (10-15°C). Initial sprint performance during intermittent high intensity exercise has also been shown to decrease after 15 min cold water

immersion (12°C) prior to exercise but any performance decrement appears transient where the cumulative performance benefit during prolonged exercise (>30-40 min) in hot conditions may outweigh early impairments to physical work capacity (Skein, Duffield, Cannon, & Marino, 2011).

Ice slurries, more commonly referred to as “slushies”, ingested before exercise have been shown to increase endurance running and cycling capacity in trained individuals by creating an effective “heat sink” to off-set metabolic heat and reduce core temperature (Ross et al., 2013). Ice slushies are more prevalent in practice than water immersion due to similar effects on endurance exercise performance in the heat without decreased appendicular muscle temperature (Bongers et al., 2015). Ice towels and vests placed on the torso or head/neck prior to exercise have also been shown to increase endurance cycling, rowing and running performance although the towel and vest method decreases skin but not core temperature (Figure 1.7). However, the effectiveness of pre-cooling strategies employing iced towels and vests for high intensity endurance performance in the heat has not been widely replicated in other contexts including intermittent sprint activity and team sport performance (Henderson, Christmas, Stevens, Coutts, & Taylor, 2020; Minett, Duffield, Marino, & Portus, 2011; Ross et al., 2013).









To maximise pre-cooling for reduction in thermal strain and subsequent increases in endurance exercise performance, the concomitant use of internal and external cooling methods may be optimal (Bongers et al., 2015; Ross et al., 2013; Ross et al., 2011). The mixed methods approach pre-exercise may be the most effective way to limit the manifestation of physiological strain during exercise in hot conditions due to the intensive cooling of the core and skin that ensues (Angel Rodriguez et al., 2020; Bongers et al., 2015). Common mixed method approaches include use of ice slushies and ice vests or cold-water immersion pre-exercise and

ice garments including towels, vests or collars during exercise. However, more studies are needed to determine the optimal mixed method combination and the most practical methods to use in competition (Bongers et al., 2017). Moreover, due to the transient nature of pre-cooling strategies and attenuated effects as duration of exercise increases, a combination of pre- and per-cooling may be required to ensure optimal performance for prolonged endurance exercise bouts (Bongers et al., 2017; Stevens et al., 2017). There may be a moderate effect for improved performance with combined cooling methods (Hedges  $g$  0.63; Bongers et al., 2017) compared to pre- versus per-cooling alone (Figure 1.7) but more studies are needed due to the short duration of exercise performance tests and differences in methodologies between studies (Bongers et al., 2017; Stevens et al., 2017).







### **1.5.2 Per-Cooling**

Per-cooling includes many of the same methods as pre-cooling and has been shown to increase endurance exercise performance by ~9% (Figure 1.7; Bongers et al., 2017). A moderate improvement in performance is evident during steady-state, self-paced exercise which replicate the extended cycling bout associated with road cycling races or triathlon (Ruddock et al., 2017). Per-cooling ice slushies and vests have been shown to reduce the evaporative requirement at a given exercise intensity by attenuating the increase in core temperature or the rate at which local skin temperature is elevated during exercise, respectively (Tyler et al., 2015). Moreover, there is evidence showing per-cooling using a custom garment applied to the neck reduces thermal sensation and rating of perceived exertion during prolonged exercise despite unchanged mean core or skin temperature, heart rate or whole body sweat rate (Lee et al., 2014; Ruddock et al., 2017; Tyler, Wild, & Sunderland, 2010). This indicates that per-cooling may

suppress the dysregulation of exercise intensity by the purported “central governor” through reducing perception of heat stress (Tucker et al., 2006).

Method	Pre-Cooling			Per-Cooling				
Modality								
Physiological and Perceptual Response	↓ Core Temperature			↓ Core				↓ Core
	↓ Skin Temperature				↓ Skin			
	↓ Thermal Sensation				↓ Thermal Sensation			
Mean Performance Effect (Hedges g)	5.7% (0.44)			9.3% (0.35)				
	6.3% (0.40)	6.5% (0.49)	3.4% (0.19)	5.7% (0.88)	11.1% (0.67)	18.5% (0.54)	6% (0.33)	17% (0.30)

					
Ice slushie/slurry	Cold water immersion	Ice vest/cooling packs	Facial water spray/wind	Menthol ingestion/spray	Acetaminophen ingestion

**Figure 1.7** Summary of the physiological, perceptual and performance effects of common pre-cooling (ice slushie/slurry, cold water immersion, ice vest/cooling packs) and per-cooling (ice slushie/slurry, ice vest/cooling packs, facial water spray, menthol ingestion/spray, acetaminophen ingestion) methods on endurance exercise in hot ( $T_a \geq 30^\circ\text{C}$ ) conditions. Mean performance effect compared to a control condition in the same environmental conditions is reported as Hedges g effect size. Pooled mean performance effect is reported for both pre-cooling and per-cooling methods adapted from Bongers et al. (2017). Mean performance effect is also adapted from Bongers et al. (2017) for ice slushie/slurry (pre- and per-cooling), cold water immersion and ice vest/cooling packs (pre- and per-cooling). Mean performance effect for menthol is adapted from Jeffries & Waldron (2019) and performance effect for acetaminophen ingestion adapted from Mauger et al. (2014). Darker green shading indicates larger effect size.

During competition it is difficult to use garments or slushies due to a lack of accessibility to the athlete or infrastructure at the event such as freezers or ice chests (Racinais et al., 2021). Accordingly, a more practical per-cooling method such as spraying the face may be appropriate, and a similar ergogenic effect using face spray during 5 km running time-trial compared to cold water immersion in 23-24°C for 30 min has been reported (Stevens, Kittel, et al., 2017). The use of menthol as a topical ointment or a mouth-rinse to attenuate the increase in thermal sensation whilst exercising in the heat may also increase exercise capacity and performance (6%; Eccles, 2000; Jeffries & Waldron, 2019; Schlader et al., 2011a; Stevens et al., 2016). Nonetheless, the practical utility of these per-cooling methods is unclear, and there is limited scientific or anecdotal evidence indicating widespread use in competition (Racinais et al., 2021). Consequently, pharmaceuticals that could be ingested or applied prior to training/competition with therapeutic actions that promote per-cooling effects would provide sustained benefits to performance with low burden of application for athletes.

A common analgesic and antipyretic pharmaceutical with widespread use in the general population is acetaminophen (also known as paracetamol). Acetaminophen has been proposed as an inhibitor of cyclo-oxygenase (COX) enzymes in the muscle and at various sites in the central nervous system (Anderson, 2008). When core temperature increases during exercise (Bradford, Cotter, Thorburn, Walker, & Gerrard, 2007), hot conditions (Esh et al., 2021), or fever (Grösch, Niederberger, & Geisslinger, 2017), prostaglandins are released by COX enzymes which act on nociceptive receptors causing the sensation of pain (Grösch et al., 2017). Other COX inhibitors have been used previously to reduce core temperature during, but not prior to, exercise (Bradford et al., 2007). Given its similar mechanism of action as a COX inhibitor, acetaminophen is a legal substance (World Anti-Doping Agency, 2021) which may have per-cooling effects. Whether ergogenic effects of acetaminophen ingested prior to endurance exercise could approach those of other currently employed cooling strategies has

yet to be established (Esh, Mauger, Palfreeman, Al-Janubi, & Taylor, 2017; Mauger et al., 2014).

There are limited data on the interaction between dose and plasma acetaminophen concentration in humans. In resting humans, acetaminophen ingestion of 20 mg·kg lean body mass resulted in a peak acetaminophen concentration of  $14 \pm 4 \text{ ug}\cdot\text{mL}^{-1}$  80-100 min after ingestion (Foster, Mauger, Thomasson, White & Taylor, 2016) and the half-life of 1-1.5 mg is 1.5-4 h in humans (Esh et al., 2017). Acetaminophen ingestion of 20 mg·kg lean body mass has been shown to reduce core temperature after 30 min, an effect that was most evident ( $-0.2^{\circ}\text{C}$ ) at ~120 min post-ingestion (Foster et al., 2016). Therefore, ingestion 90-120 min pre-exercise may be optimal for peak circulating acetaminophen. Studies on the effect of acetaminophen on exercise performance to date have been limited but some data indicate an ergogenic effect using a 1-1.5 mg dose ingested 45 min pre-exercise, albeit during exercise bouts of relatively short endurance durations (Mauger, Jones, & Williams, 2010; Mauger et al., 2014). Specifically, it has been reported that acetaminophen increased time to exhaustion at 70%  $\text{VO}_{2\text{max}}$  by 17% in hot and humid conditions (Mauger et al., 2014) and has been associated with increased cycling time trial performance (2%) in trained cyclists in temperate conditions (Mauger et al., 2010). Alternately, there is contrasting evidence showing little or no cooling and subsequent performance effects with acetaminophen ingestion using a similar dose and timing (Coombs, Cramer, Ravanelli, Morris, & Jay, 2015; Veltmeijer et al., 2017). Moreover, Coombs and co-workers have shown that metabolic heat production and heat balance is not different during sub-maximal exercise after the ingestion of acetaminophen (Coombs et al., 2015).

It is important to note that critical experimental work to determine the acetaminophen dose response and the active time-course / half-life after ingestion are lacking in the exercise context.



One study has shown exercise does not affect acetaminophen pharmacokinetics (Loniewski, Sawrymowicz, Pawlik, Wójcicki & Drozdziak, 2001) however further study to replicate such works under different environmental conditions would also be necessary to generate sufficient evidence base on the practical utility of acetaminophen as a per-cooling ergogenic aid for exercise in the heat. Nonetheless, given the challenges of implementing per-cooling to enhance performance in training and competition, acetaminophen may represent a desirable ergogenic aid for promoting exercise capacity in hot conditions with the potential to be a long-lasting, effective and practical per-cooling strategy for elite athletes.

## 1.6 Summary and Aims of this Thesis

Challenging environmental conditions are becoming more prevalent during athletic competition and training due to the globalization of sport and increased impact of climate change. Athletes and coaches desire high quality training sessions to promote adaptation for elite performance and employ intricate planning to attain peak performance in competition. Therefore, characterizing the physiological effect of varied environments on exercise performance and developing strategies for effective use of ergogenic aids to decrease the impact of thermoregulatory strain has become increasingly important. Whilst current thermal physiology literature has established the effect of divergent environmental conditions on the physiology and performance of cyclists and runners, little investigation has occurred in elite swimming particularly during outdoor swimming training or competition. Additionally, the efficiency of acetaminophen as an ergogenic aid for exercise in hot and humid conditions is equivocal and there is limited understanding about its potential effect during endurance performance. Experimental designs that can elucidate novel thermoregulatory challenges are required to develop a greater understanding of the impact of environmental conditions on elite athletes during training and competition. Accordingly, the studies within this thesis engaged elite and sub-elite swimmers and triathletes to characterise physiological and performance responses *in situ* (swimmers) in varied environmental conditions and during a simulation of hot conditions in competition (triathlon).

### 1.6.1 Aims and Hypotheses

The primary *aim* of the first experimental study was to determine whether divergent environmental conditions affected outdoor swimming training physiology and performance in elite and sub-elite swimmers. The *hypothesis* was that core and skin temperature, and thermal sensation would be reduced during outdoor swimming in colder environmental conditions and would be associated with poorer training performance.

The *aim* of the second experimental study was to test the effect of acetaminophen (paracetamol) ingestion on trained triathlete physiology and performance during steady state and time-trial endurance cycling in hot and humid conditions. The *hypothesis* was that acetaminophen ingestion would be associated with improved endurance cycling time-trial performance in the heat concomitant with a decrease in gastrointestinal temperature and thermal sensation.

.

---

## **Chapter 2**

Effect of varied environmental conditions on  
thermoregulation and outdoor training performance of  
elite and sub-elite swimmers

---

## 2.1 Abstract

Thermoregulation in running and cycling is well characterized but little is known about thermoregulation during swimming. This study aimed to determine the effect of different environmental conditions on physiological and perceptual measures and training performance during outdoor training in elite and sub-elite swimmers. Nine elite and ten sub-elite swimmers undertook training in an outdoor heated pool in COOL (wet bulb globe temperature [WBGT]=14.7°C) and WARM (WBGT=23.0°C) or COLD (WBGT=10.3°C) and HOT (WBGT=27.0°C) environmental conditions, respectively. Environmental conditions, gastrointestinal temperature ( $T_{gi}$ ), skin temperature ( $T_{sk}$ ), thermal comfort, thermal sensation and performance times were recorded throughout training sessions and analysed using repeated-measures ANOVA with alpha 0.05. Ambient temperature differed between COOL and WARM (7.9 °C,  $p<0.001$ ), and COLD and HOT (14.5 °C,  $p<0.001$ ).  $T_{sk}$  ( $p<0.001$ , ELITE: 2.8 °C, 95% CI 3.4 to 2.2 °C, SUB-E: 4.5 °C, 95% CI 5.2 to 3.7 °C) and thermal sensation (ELITE:  $p=0.012$ , 0.5 AU, 95% CI 1.1 to -0.2 AU; SUB-E:  $p=0.028$ , 0.6 AU, 95% CI 1.3 to -0.1 AU) were higher in WARM/HOT conditions compared to COOL/COLD but  $T_{gi}$  was not different. There were small improvements in swimming performance during WARM/HOT trials in elite and sub elite swimmers (ELITE: -1.7%, 95% CI -4.4 to 1.1%,  $d=0.2$ ; SUB-E: -3.2%, 95% CI -9.4 to 3.0%,  $d=0.2$ ). Skin temperature and thermal sensation vary dependent on ambient temperature despite consistent water temperature and there are small to moderate improvement in the quality of training during hot/warm compared to cold/cool seasonal conditions.

## 2.2 Introduction

It is well-known that exercise in hot environmental conditions induces thermoregulatory changes in cutaneous blood flow resulting in a reduction in performance capacity due to the cardiovascular strain associated with competing demands for blood flow at the skin and the skeletal muscle (Racinais et al., 2015). A factor that can be overlooked is that cold conditions also have the capacity to attenuate exercise performance if inadequate internal and skeletal muscle heat production reduces neural drive and alters  $\dot{V}O_2$  kinetics, reducing coordination and work performed during sprint and endurance exercise (Racinais & Oksa, 2010; Wakabayashi et al., 2018). Metabolic heat production and/or shivering thermogenesis can maintain core temperature and exercise performance in some contexts despite low skin temperature (Alhammoud et al., 2020; Holmér & Bergh, 1974), but a similar magnitude of effect for decreased endurance performance (~3%) can be observed in cold and hot environmental conditions compared to temperate conditions (Cheuvront, Carter, Castellani, & Sawka, 2005; Peiffer & Abbiss, 2011).

Athletes who train outdoors may undertake exercise year-round in highly variable environmental conditions. Moreover, the exercise environment for athletes is largely determined by available infrastructure and geographical location, and it is common for athletes to undertake training indoors so that the environment can be artificially controlled. When performance differences of ~1% may have a significant effect on results in major international swimming competitions (Pyne, Trewin, & Hopkins, 2004), maximising adaptation responses during training becomes critical during preparation for competition. Elite swimmers are a sub-group of athletes that can be exposed to variation in the training environment when training outdoors. Various cardiovascular and neuromuscular responses are known to occur to maintain allostasis in divergent environmental conditions (Nimmo, 2004; Trangmar & González-Alonso, 2019). However, there is a paucity of data currently available on the impact of seasonal

changes in ambient temperature on thermoregulation and the quality of training during outdoor swimming.

Whilst optimal environmental conditions are known for elite athletes in running and cycling (Ely, Cheuvront, Roberts, et al., 2007; Galloway & Maughan, 1997; Guy et al., 2015), the seminal paper by Robinson and Somers (1971) is the only data describing the effect of environmental conditions on swimming performance in elite athletes. They concluded that water temperature between 28°C and 30°C was optimal for sprint swimming but no studies have been undertaken to corroborate these findings, and ambient temperature was not considered in the data analysis. Low to moderate intensity swimming has been shown to reduce skin and core temperature at higher water temperatures than equivalent ambient environments due to the greater heat transfer capacity of water compared to air (Cheung, 2010; McArdle et al., 1976; Nadel et al., 1974). Additionally, skin temperature and thermal sensation has been purported to alter exercise performance (Schlader, Stannard, & Mündel, 2010) but the effect of the aquatic environment on skin temperature and perceptions of thermal sensation/comfort and any association with altered performance is unclear. Moreover, the impact of environmental conditions on physiological and perceptual responses, and the work performed when elite swimmers undertake outdoor training is currently unknown. Therefore, the aim of the present study was to determine the effect of varied seasonal environmental conditions on outdoor training performance, thermal physiology and perception in elite swimmers during a high intensity training session and a sprint training session. The hypothesis was that core and skin temperature, and thermal sensation would be reduced during outdoor swimming in colder environmental conditions and would be associated with poorer training performance.

## 2.3 Methods

### 2.3.1 Participants

A convenience sample of nine international (elite) and ten national (sub-elite) level participants from a high-performance swimming squad volunteered to take part in the study (Table 2.1). Due to competition schedules and illness  $n = 2$  elite swimmers and  $n = 1$  sub-elite swimmers did not complete the data collection and were excluded from all statistical analyses. Informed written consent for participation was provided by all athletes and ethical approval was granted by the Bond University Human Research Ethics Committee (GW02856).

**Table 2.1** Participant characteristics.

	Elite	Sub-Elite
Males/Females	6 / 3	7 / 3
100m Freestyle Personal Best (FINA Points)	908 $\pm$ 43	873 $\pm$ 38
100m Freestyle Personal Best (s)	53.8 $\pm$ 4.2	55.2 $\pm$ 2.9
Age (years)	22.5 $\pm$ 2.0	19.5 $\pm$ 0.9
Height (cm)	178.3 $\pm$ 7.9	181.6 $\pm$ 4.9
Body Mass (kg)	69.9 $\pm$ 10.5	73.9 $\pm$ 6.0
Lean Muscle Mass (kg)	56.6 $\pm$ 9.8	57.7 $\pm$ 6.9
Body Fat (%)	16.2 $\pm$ 3.7	15.6 $\pm$ 7.7
Body Surface Area (m <sup>2</sup> )	1.9 $\pm$ 0.2	1.9 $\pm$ 0.1
BSA:mass (cm <sup>2</sup> ·kg <sup>-1</sup> )	269 $\pm$ 15	264 $\pm$ 9

Data are mean  $\pm$  standard deviation, FINA = Federation Internationale de Natation, BSA = body surface area



### **2.3.2 Experimental Overview**

The experimental approach employed a within participant study design with trials undertaken in warm/hot (Elite: February 2020; Sub-Elite: February 2020) and cool/cold (Elite: October 2019; Sub-Elite: July 2020) environmental conditions. Trivial performance changes occur across 3-4 months in highly trained swimmers ( $\sim 0.5\%$ , 100m freestyle time = 0.24 s; Pyne, Trewin & Hopkins, 2004) therefore it was assumed that training status was similar between trials. Participants completed a routine training session designed and conducted by a high-performance swimming coach where the same session was replicated within elite and sub-elite groups. The session prescription (Table 2.2 and Table 2.3) contained high intensity swimming interspersed with short duration rest periods for the elite swimmers, and sprint repetitions with long rest intervals for sub-elite swimmers. The session completed by elite swimmers was designed to maximise metabolic adaptation whilst the session for sub-elite swimmers was designed to train maximal speed.

### **2.3.3 Preliminary testing**

Participants reported to the laboratory for anthropometric assessment. Body mass was determined using electronic scales (WM204, Wedderburn, Australia) and height using a wall-mounted stadiometer (Harpden stadiometer, Holtain Limited, UK). Dual energy x-ray absorptiometry was used to determine body composition while air displacement plethysmography was used to quantify body volume and surface area.

Participants arrived at the laboratory after a  $\sim 4$  h fasting period before undergoing a dual energy x-ray absorptiometry (DEXA) scan (Lunar Prodigy DXA machine, GE Healthcare, USA). The scan was performed by a licensed practitioner using methods described previously (Nana, Slater, Stewart, & Burke, 2015). Briefly, participants clothed in their swimsuit lay in a supine position, palms flat and separated from the torso with feet together. Post-scan segmentation

was identified using the proprietary software (GE encore 2016 software, GE Healthcare, Madison, WI, USA).

Air displacement plethysmography was performed using a BODPOD® (Cosmed, USA) according to the manufacturer's instructions. Briefly, participants were clothed in their swimsuits and wore a swim-cap during the scan. Air-displacement plethysmography was used to determine body volume (L) with body density being calculated using the equation of Siri (1956) and lung volume predicted using the equation of Crapo, Morris, Clayton, & Nixon (1982).

### **2.3.4 Testing Procedures Overview**

All experimental trials were undertaken during morning training sessions (Elite: 0630-0830, Table 2.2; Sub-Elite: 0530-0730, Table 2.3) at an outdoor venue and 50 m heated pool. During each training session environmental conditions (water temperature, ambient temperature, relative humidity, solar radiation and wind speed) and core temperature were collected continuously throughout the session whilst skin temperature was collected poolside before, during and after the session using a thermal imaging camera. Perceived thermal comfort and sensation were collected throughout the session. Body mass and drink bottle mass were obtained before and after the session to assess fluid balance. Due to the high-performance nature of the swimming groups and associated scheduling constraints, the menstrual cycle phase was unable to be matched for female participants. Additionally, during the COOL trial training was interrupted (~20 min) for safety due to a tropical storm. During this time swimmers exited the pool, were allowed to towel-dry and clothe themselves as they wished. After the break, swimmers completed a standardised ~5 min warm up before resuming their training session. The interruption was not replicated for the WARM trial.

**Table 2.2** Swim training session prescription including high intensity interval training for elite swimmers (n = 9).

	Warm Up	Main Set	Endurance Set	Cool Down	Total
Distance (km)	2.4	2.2	1.1	1.2	SPR = 5.6 END = 6.9
Prescription	<p>400m + 300m + 200m + 100m {100m freestyle + 100m backstroke} with fins on 1:25/100 pace</p> <p>16 × 50m on 1:00 1-8 medley order 9-16 odd rep drill Even repetitions build with fins</p> <p>4 × 100m { 25m underwater 25m build into turn 50m drill</p> <p>4 × 50m descending (RPE 5, 6, 7, 8-10) on 1:00</p>	<p>3 x 100m 50m @ 9/10 RPE on 1:00 100m OR 200m steady on 2:30 pace</p> <p>Middle distance = 100m on 2:30 Long distance = 200m on 2:30</p> <p>100m repetition cycle times:</p> <p>Set 1 = 1:30 at 30 beats below HR max Set 2 = 1:40 at 25 beats below HR max Set 3 = 1:50 at 20 beats below HR max Set 4 = 2:00 at 15 beats below HR max</p>	<p>Set 5-6 Main Set</p> <p>2:00 cycle at 15 beats below HR max</p>	<p>6 × 200m on 4:00</p> <p>odd rep kick (20m maximal each 100) even 50 drill (use fins) then 50m scull</p>	

RPE = modified rating of perceived exertion.

**Table 2.3** Swim training session prescription including sprint training repetitions for sub-elite swimmers (n = 10).

IM = individual medley order.

	Warm Up	Main Set	Endurance Set	Cool Down	Total
Distance (km)	3.0	0.4	2.9	1.2	SPR = 4.6 END = 7.5
Prescription			800m strong negative split on 12:00	12 × 100m fins on 1:30	
	800m freestyle/IM × 50 on 12 with fins		8 × 50m fast on 40		
	8 × 50m breath control (4, 6, 8, 10) on 60		600m strong negative split on 9:00	1) freestyle (technique)	
	400m freestyle/IM × 50 on 6:30 with fins				
	4 × 50m fly kick on back on 60		6 × 50m fast on 45		
	200m IM on 3:30		400 strong negative split on 6:00	2) IM (double underwater pull out)	
	2 × 50m bubbles on 60		4 × 50m fast on 50		
	3 × { 150m descend 50s 1 – 3 on 2:30 100m steady on 1:45 50m 20/30/40 stroke count on 75		200 strong negative split on 3:00	3) butterfly kick on back (20m underwater each wall)	
			2 × 50m fast on 60		

### **2.3.5 Dietary Standardisation**

Upon arrival to each trial, participants provided a urine sample collected mid-stream upon waking which was analysed using a refractometer (PAL-10S, Atago, Japan) to determine hydration status via urine specific gravity. For each trial, participants were required to record dietary intake and timing in a food diary from 1500 h the day prior to the trial until arrival. These were collected and redistributed before trial two and participants were asked to replicate food and fluid intake to ensure dietary intake was similar between trials.

### **2.3.6 Environmental Conditions**

The training location at which data were collected was a coastal, sub-tropical region (28° S, 153° E) in Australia. Water temperature ( $T_w$ ) was measured directly using a thermochron (iButton; Maxim Integrated, USA) located ~50 cm below the water surface. Ambient temperature ( $T_a$ ) and relative humidity (RH) was measured at 60 s intervals using a commercial monitor (Kestrel 5400; Kestrel Instruments, USA). Solar radiation (SR) was measured every 30 s using a pyranometer (MP-100; Apogee Instruments, USA). All environmental conditions data was then calculated into 30 min averages for analysis. Wet-bulb globe temperature (WBGT) was calculated using the Liljegren method (Liljegren, Carhart, Lawday, Tschopp, & Sharp, 2008).

### **2.3.7 Performance Times**

Performance time was a primary outcome of the study and was measured during the main set of experimental trials for each 100 m or 50 m repetition. Each repetition was timed by an experienced swimming coach or assistant coach using a handheld stopwatch (SVAS009; Sieko, Japan, TEM=0.36%; McGowan et al., 2017) as this is the typical method used during training and the error of measurement is lower than meaningful performance changes (0.5%). For analysis in the elite group, each participant's average 100 m time for each set was used.

### **2.3.8 Gastrointestinal Temperature**

Gastrointestinal temperature was a primary outcome of the study and was collected as a measure of deep body temperature using an uncalibrated ingestible thermistor pill (e-Celsius Performance; Bodycap, France, SEM=0.04°C, ICC=1.00, Bongers et al., 2018) due to its practicality in an applied swimming setting. Data were recorded at 30 s intervals which were converted into 60 s epochs for analysis. Participants ingested the pill 8-9 h prior to arrival for experimental trials. For the elite group, only data from the first 80 min was statistically analysed due to the 20-min delay that occurred during the COLD trial. Additionally, n = 2 elite participants completed a competition specific warm up in one trial therefore their data was excluded from analysis.

### **2.3.9 Skin Temperature**

Surface temperature ( $T_{\text{surface}}$ , TEM=0.2°C, CV=1.3%, r=0.96) was a primary outcome of the study and was assessed using a thermal imaging camera (FLIR SC660; Flir Systems, USA) upon arrival, immediately pre session, after the main set and post session. Thermal imaging was used to collect body surface temperature data despite poor agreement with conductive devices (Bach, Stewart, Disher, & Costello, 2015) because it is a reliable, convenient alternative to thermistors and thermochrons which are difficult to attach to swimmers and may malfunction with prolonged exposure to water. To complete the data collection with minimal temporal delay from exiting the pool to image capture (~2 min), thermographic images were a) taken outdoors and b) the camera was not positioned perpendicular to all areas of interest. Therefore, thermographic images were collected following 13 of the 15 recommendations of Moreira et al. (2017). Participants were instructed to stand in the anatomical position on marked lines 3.5 m away from the thermal imaging camera in an allocated outdoor area protected from

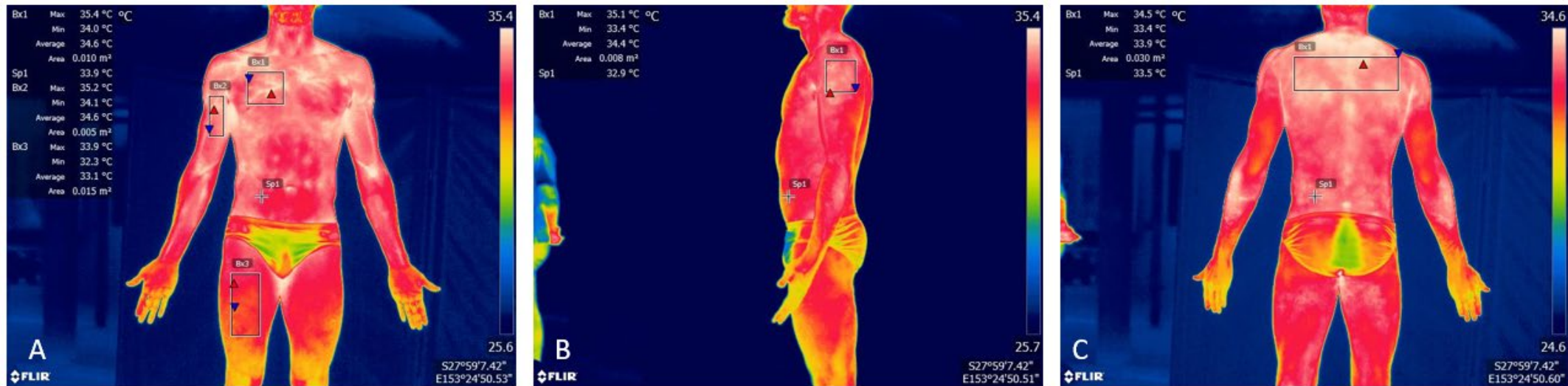
wind and solar radiation ~ 5 m from poolside. For images captured after water immersion, participants were instructed to towel dry as quickly as possible (~ 2 min) using patting rather than rubbing to minimise micro-abrasion on the skin. The pre-session images were obtained after an initial 5 min resting period in the water submerged to the level of the shoulders. Thermal images of the anterior, left lateral and posterior aspects of the body were captured once sequentially between the shoulders and knees at each time point. Image number was recorded for reference in analysis. Thermal images were then downloaded from the thermal imaging camera, saved as jpeg files, and uploaded to the proprietary software (FLIR Tools; FLIR Systems, USA). Software settings were adjusted to account for the appropriate emissivity index for dry skin (0.98) and distance from the camera (3.5m). The areas of interest (AOIs) covered  $3.4 \pm 0.1\%$  body surface area (BSA) and were defined as the chest ( $0.01\text{m}^2$ , 0.5% BSA), bicep ( $0.005\text{m}^2$ , 0.25% BSA), thigh ( $0.015\text{m}^2$ , 0.75% BSA), upper back ( $0.03\text{m}^2$ , 1.5% BSA) and deltoid ( $0.008\text{m}^2$ , 0.4% BSA). Bicep, chest, and thigh AOIs were identified using images of the anterior surface of the body, deltoid AOI was identified using the image of the lateral surface and back AOI identified using images of the posterior surface. AOIs were able to be visually placed using a rectangle on the surface of the body according to the criteria in Table 2.4. The dimensions of each area of interest (pixel  $\times$  pixel) from the first set of thermal images were recorded for each individual and then replicated for each subsequent set of thermal images.

Mean temperature for the AOI was recorded as skin temperature for a given region and for the total body was calculated using the following mean skin temperature equation (Roberts, Wenger, Stolwijk, & Nadel, 1977):

$$\text{Mean Skin Temperature (}^{\circ}\text{C)} = 0.43 (\text{Chest}) + 0.25 (\text{Deltoid}) + 0.32 (\text{Thigh}) \quad \text{Equation 2.3}$$

**Table 2.4** Criteria for area of interest assessment subsequently used to quantify skin temperature using the thermal imaging camera.

Area of Interest	Bicep	Chest	Thigh	Deltoid	Back
Criteria	<ul style="list-style-type: none"> <li>• Top of the rectangle horizontally aligned with axilla</li> <li>• Mid-bicep in the middle of the rectangle</li> </ul>	<ul style="list-style-type: none"> <li>• Top of the rectangle aligned with the clavicle</li> <li>• Left-hand side aligned along the sternum</li> <li>• Rectangle should not overlap swimsuit</li> </ul>	<ul style="list-style-type: none"> <li>• Middle of right thigh in the centre of the rectangle</li> <li>• No longer than 85 pixels</li> </ul>	<ul style="list-style-type: none"> <li>• Top of the rectangle in line with acromion process</li> <li>• Bottom of the rectangle in line horizontally with axilla</li> <li>• Rectangle is the width of the arm</li> </ul>	<ul style="list-style-type: none"> <li>• Middle of the box in line vertically with the spine</li> <li>• Bottom of rectangle in line with axilla.</li> </ul>



**Figure 2.1** Representative thermal images for analysis of surface temperature of the (A) anterior surface, (B) the lateral surface and (C) the posterior surface for each participant.



### 2.3.10 Perceptual Measures

Perceived thermal comfort on a 4-point Likert scale (1 comfortable, 4 uncomfortable; Gagge, Stolwijk, & Saltin, 1969) and perceived thermal sensation on a 17-point Likert scale (0.0 unbearably cold, 4.0 neutral, 8.0 unbearably hot; Young, Sawka, Epstein, Decristofano, & Pandolf, 1987) were assessed verbally after reference to the visual scale. Participants were familiarized with each scale during swimming prior to the first experimental trial. Data was obtained intermittently and at matched time-points (arrival, pre-session, post warm up, after each main set repetition, post session) during each trial. Data was collected whilst immersed in water except for arrival and post session.

### 2.3.11 Fluid Balance

Participants were weighed towel-dried in their swimsuits to determine body mass pre and immediately post each trial (WM204; Wedderburn, Australia). If participants voided their bladder during the session, they were weighed immediately before and after to record excreted fluid loss. Participants' drink bottles were weighed using portable scales (KD-192, Tanita, Japan) before and after the trial to determine total fluid consumption. Whole body sweat loss (WBSL) was calculated using the following formula:

$$\text{WBSL (L)} = (\text{Body Mass PRE (kg)} - \text{Body Mass POST (kg)}) + \text{Total Fluid Consumption (L)} - \text{Urine Loss (L)} \quad \text{Equation 2.4}$$

Whole body sweat rate (WBSR) was determined using the following equation:

$$\text{WBSR} \left( \frac{\text{L}}{\text{h}} \right) = \frac{\text{WBSL (L)}}{\text{Exercise Duration (h)}} \quad \text{Equation 2.5}$$

### 2.3.12 Statistical Analyses

Statistical analyses were conducted independently for each group (elite and sub-elite). Physiological, performance and perceptual measures were analysed using repeated-measures

(time  $\times$  trial) analysis of variance (ANOVA). Sphericity was tested using Mauchly's test and when sphericity was violated a Greenhouse-Geisser correction was used. When significant interactions were observed, post-hoc pairwise comparisons were conducted using a Bonferroni correction. Fluid balance and USG measurements were analysed between trials using paired Student t-tests. Environmental conditions were compared between trials using a Student independent samples t-test. Analyses of  $T_{gi}$  occurred until the extended break for elite (80 min) and the end of the sprint session for sub-elite (120 min). Effect sizes were calculated using Cohen's d with thresholds for small (0.2), moderate (0.5) and large (0.8) interpreted according to Cohen (2013). Statistical analyses were conducted using GraphPad Prism (version 8.4.2, GraphPad Software Inc, USA) and the open access software JASP Version 12.2.0 ([www.jasp-stats.org](http://www.jasp-stats.org), Netherlands). Data are mean  $\pm$  standard deviation or mean  $\pm$  95% confidence interval and statistical significance was set at  $P < 0.05$ .

## 2.3 Results

### 2.3.1 Environmental Conditions

Mean  $T_a$  and WBGT was higher in the WARM compared with COOL conditions during training for elite swimmers ( $\Delta T_a$  7.9°C,  $\Delta$ WBGT 8.3°C,  $p < 0.001$ ; Table 2.5). There were only small changes in  $T_a$  and WBGT during the COOL ( $\Delta T_a$  -0.6°C,  $\Delta$ WBGT -0.7°C) and WARM trials ( $\Delta T_a$  0.1°C,  $\Delta$ WBGT 0.5°C). The mean  $T_w$ , relative humidity, solar radiation and wind speed were similar between and during trials.

The mean  $T_w$ ,  $T_a$ , relative humidity (RH) and WBGT were higher in HOT compared to COLD training sessions for sub-elite swimmers ( $\Delta T_w$  0.2°C,  $\Delta T_a$  14.5°C,  $\Delta$ RH 10.9%,  $\Delta$ WBGT 16.7°C,  $p < 0.001$ ; Table 2.5). Throughout the  $\sim 2$  h data collection period in both trials  $T_a$  (HOT:  $\Delta$  1.5°C; COLD:  $\Delta$  1.2°C), WBGT (HOT:  $\Delta$  7.3°C; COLD:  $\Delta$  3.3°C) and solar radiation (HOT:  $\Delta$  423 W·m<sup>-2</sup>; COLD:  $\Delta$  108 W·m<sup>-2</sup>) increased whereas RH increased during the COLD but not the HOT trial (HOT:  $\Delta$  -0.3 %; COLD:  $\Delta$  4.2 %, Table 2.5).

**Table 2.5** Mean environmental conditions during outdoor swimming training in elite swimmers (n = 7, 0630-0830 h) during a COOL trial completed in spring and a WARM trial completed in summer, and in sub-elite swimmers (n = 8, 0530-0730 h) during a HOT trial completed in summer compared to a COLD trial completed in winter. Data are mean ( $\pm$  standard deviation) and were analysed using Student's independent samples t-test.

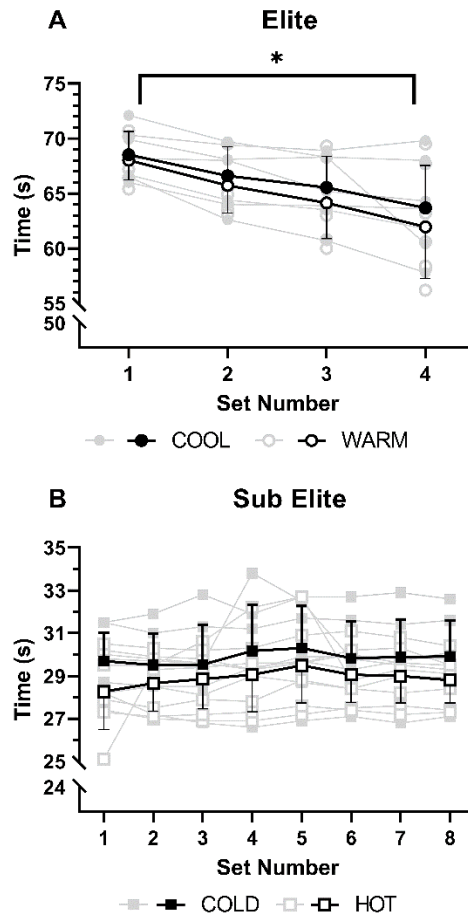
	Elite			Sub-elite		
	COOL	WARM	p-value	COLD	HOT	p-value
T <sub>w</sub> (°C)	28.2 (0.03)	28.2 (0.04)	0.207	28.2 (0.05) <sup>b</sup>	28.4 (0.00)	< 0.001
T <sub>a</sub> (°C)	15.5 (0.4) <sup>a</sup>	23.4 (0.2)	< 0.001	11.8 (0.9) <sup>b</sup>	26.3 (0.9)	< 0.001
Relative Humidity (%)	97.4 (4.7)	99.0 (1.7)	0.847	83.7 (1.9) <sup>b</sup>	72.8 (1.9)	< 0.001
Absolute Humidity (g·m <sup>3</sup> )	12.7 (0.5)	20.8 (0.8)	< 0.001	8.6 (0.6)	18.4 (0.7)	< 0.001
Solar Radiation (W·m <sup>-2</sup> )	30.1 (28.3)	-	-	37.0 (50.2)	248.8 (186.0)	0.070
WBGT (°C)	14.7 (0.4) <sup>a</sup>	23.0 (0.2)	< 0.001	10.3 (1.8) <sup>b</sup>	27.0 (3.3)	< 0.001

<sup>a</sup> , significantly different to WARM (p < 0.001); <sup>b</sup> , significantly different to HOT (p < 0.001); T<sub>w</sub>, water temperature, T<sub>a</sub>, ambient temperature, WBGT, wet bulb globe temperature.

### 2.3.2 Performance

Mean performance time improved for elite swimmers between Set 1 and Set 4 (main effect:  $p < 0.001$ , COOL:  $-4.9 \pm 3.2$  s,  $d = 1.5$ ; WARM:  $-6.1 \pm 3.4$  s,  $d = 1.8$ ) within each trial but mean performance times during the main training set were not significantly different between trials ( $p = 0.767$ , WARM-COLD:  $1.1 \pm 4.3$  s,  $1.7 \pm 6.5\%$ ,  $d = 0.26$ , Figure 2.2A). Specifically, each set within the WARM and COOL trial was faster than the previous set ( $p = 0.01$  to  $0.04$ ).

There was no significant difference in performance times ( $p = 0.944$ ,  $1.0 \pm 2.2$  s,  $3.3 \pm 7.4\%$ ,  $d = 0.60$ , Figure 2.2B) between COLD and HOT trials for sub-elite swimmers. Additionally, there were no differences between each 50 m sprint time in the HOT compared with COLD trial ( $\Delta -0.7$  to  $-1.4$  s,  $d = -0.3$  to  $-0.6$ ,  $\Delta\% 2.3$  to  $4.8\%$ , Figure 2.2B).

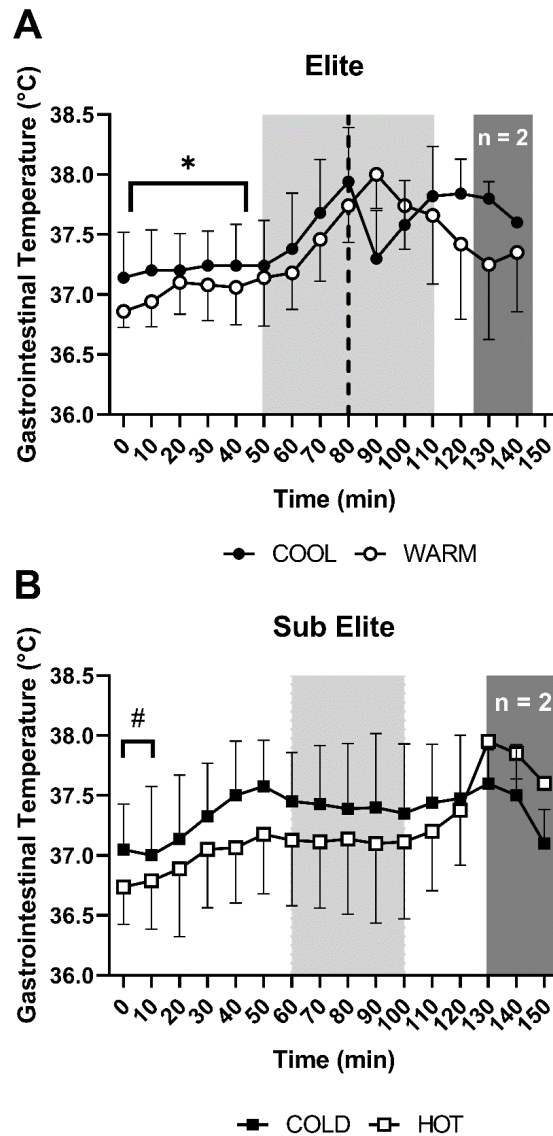


COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions and (B) sub-elite swimmers undertaking a sprint training session in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions. Elite swimmers completed a total distance range of 5.6-6.9 km including four sets of three  $\times$  100 m efforts whilst sub-elite swimmers completed a session with total distance range 4.6-7.5 km including eight  $\times$  50 m sprint beginning every 5 min during the main set. Data are mean  $\pm$  95% confidence interval (A & B;  $n = 7$ ) and were analysed using a two-way repeated measures ANOVA (time  $\times$  trial) with Bonferroni post-hoc procedure for multiple comparisons.

### 2.3.3 Gastrointestinal Temperature

There was a main effect of time ( $p < 0.001$ ) for  $T_{gi}$  of elite swimmers during warm up (COOL:  $0.1 \pm 0.2^{\circ}\text{C}$ ,  $d = 0.43$ ; WARM:  $0.3 \pm 0.4^{\circ}\text{C}$ ,  $d = 0.79$ , Figure 2.3A) and large increases during high intensity swimming (sets 1-3) in COOL ( $0.7 \pm 0.3^{\circ}\text{C}$ ,  $d = 2.4$ , Figure 2.3A) and WARM ( $0.6 \pm 0.4^{\circ}\text{C}$ ,  $d = 1.6$ , Figure 2.3A). There were no differences in  $T_{gi}$  of elite swimmers between the COOL and WARM trials ( $p = 0.950$ ). During the main set, the maximum mean  $T_{gi}$  recorded was similar between both trials (COOL:  $38.0 \pm 0.4^{\circ}\text{C}$ , WARM:  $38.1 \pm 0.3^{\circ}\text{C}$ ,  $p = 0.855$ ).

There was no difference in  $T_{gi}$  of sub-elite swimmers between COLD and HOT trials ( $p = 0.841$ ; Figure 2.3B). A main effect of time was evident during each trial ( $p < 0.001$ ) with a large effect associated with the increase in  $T_{gi}$  post warm up (50 min;  $\Delta 0.5 \pm 0.2^{\circ}\text{C}$ ,  $d = 2.2$ ,  $p < 0.001$ ), during the main set (60-100 min;  $\Delta 0.4 \pm 0.2^{\circ}\text{C}$ ,  $d = 1.4-1.8$ ,  $p < 0.001$ ) and post session (150 min;  $\Delta 0.4^{\circ}\text{C} \pm 0.2$ ,  $d = 1.9$ ,  $p < 0.001$ ) compared to pre-session ( $37.0 \pm 0.4^{\circ}\text{C}$ ) in COLD conditions.  $T_{gi}$  also increased between pre-session, post warm up ( $\Delta 0.4 \pm 0.2^{\circ}\text{C}$ ,  $d = 1.8$ ,  $p < 0.001$ ) and post session ( $\Delta 0.6 \pm 0.2^{\circ}\text{C}$ ,  $d = 2.3$ ,  $p < 0.001$ ) in HOT conditions. During the main set  $T_{gi}$  was higher than pre-session for all repetitions in both trials but was not significant for repetition seven of the set (Mean  $\Delta 0.4 \pm 0.03^{\circ}\text{C}$ ,  $d = 1.5 \pm 0.1$ ,  $p = 0.009$  to  $0.001$ , repetition 7  $\Delta 0.3 \pm 0.2^{\circ}\text{C}$ ,  $d = 1.2$ ,  $p = 0.07$ ).



**Figure 2.3** Gastrointestinal temperature during outdoor swim training for (A) elite swimmers undertaking a high intensity interval training session in COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions and (B) sub-elite swimmers undertaking a sprint training session in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions. Elite swimmers completed a total distance range of 5.6-6.9 km including four sets of three  $\times$  100 m efforts whilst sub-elite swimmers completed a session with total distance range 4.6-7.5 km including eight  $\times$  50 m sprint beginning every 5 min during the main set. Data are mean  $\pm$  standard deviation (A;  $n = 5$ , B;  $n = 8$ ) and were analysed using a two-

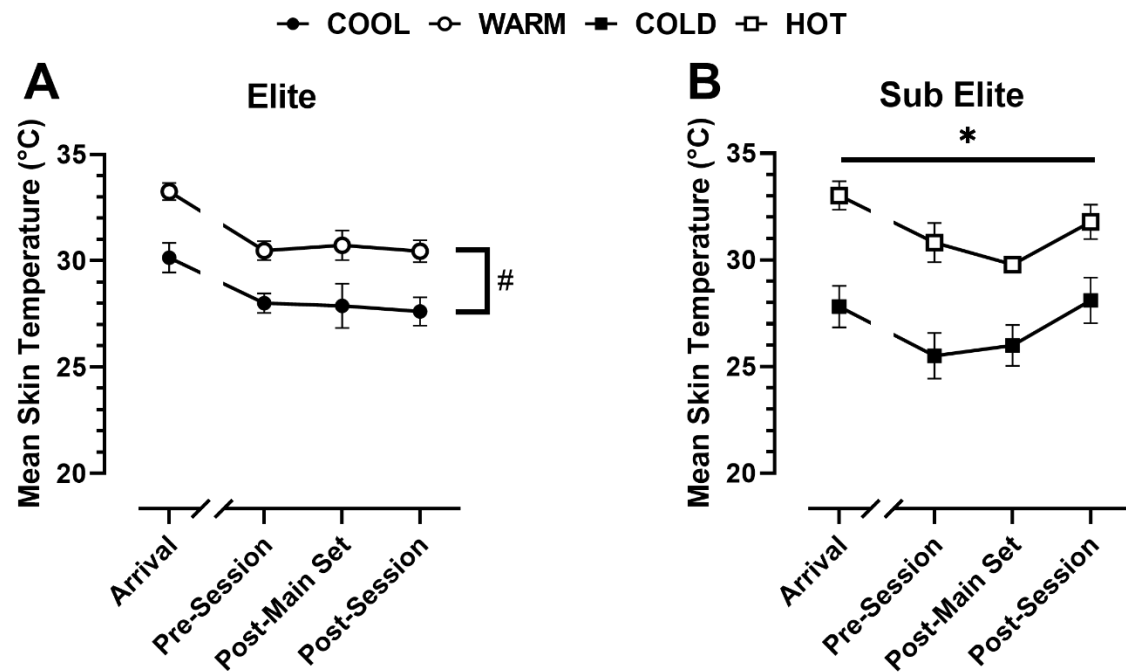


way repeated measures ANOVA (time  $\times$  trial) with Bonferroni post-hoc procedure for multiple comparisons. In A, the dashed line shows the prolonged rest period during training whilst in both A and B, light grey shading shows the main set period and dark grey shows extended training undertaken by endurance swimmers only ( $n = 2$ ). \*, different to 50-80 minutes ( $p < 0.05$ ), # different to all other time-points ( $p < 0.05$ ).

### 2.3.4 Mean Skin Temperature

There was a main effect of trial showing lower  $T_{sk}$  in COOL ( $-2.8 \pm 0.5$  °C,  $d=5.1$ ,  $p<0.001$ ) but no interaction effects for  $T_{sk}$  ( $p=0.582$ , Figure 2.4A). There was a large decrease in  $T_{sk}$  of elite swimmers from arrival to pre-training in each trial (COOL:  $\Delta -2.1 \pm 0.9$  °C,  $d=2.4$ ; WARM:  $\Delta -2.8 \pm 0.5$  °C,  $d=5.3$ ,  $p<0.001$ ) and a small effect for the decrease from pre-training to post-training in COOL ( $\Delta -0.4 \pm 0.9$  °C,  $d=0.44$ ) that was not apparent in the WARM trial ( $\Delta -0.03 \pm 0.7$  °C,  $d=0.06$ ).

There was a large increase in  $T_{sk}$  of sub-elite swimmers in HOT compared to COLD trial conditions ( $p<0.001$ , Figure 2.4B) with the largest differences between arrival ( $\Delta 5.2 \pm 1.2$  °C,  $d=4.4$ ) and pre-session ( $\Delta 5.3 \pm 1.4$  °C,  $d=3.8$ ) timepoints. The difference in  $T_{sk}$  from arrival and pre-session was reduced in a similar manner for each trial after the main set ( $\Delta 3.8 \pm 1.0$  °C,  $d=3.8$ ) and post session ( $\Delta 3.7 \pm 1.3$  °C,  $d=2.8$ ). In the COLD trial,  $T_{sk}$  pre-session ( $\Delta -2.3 \pm 0.8$  °C,  $d=3.1$ ,  $p<0.001$ ) and post-main set ( $\Delta -1.8 \pm 1.0$  °C,  $d=1.9$ ,  $p=0.007$ ) was less than upon arrival whilst in HOT conditions  $T_{sk}$  upon arrival was higher than all timepoints (PRE:  $\Delta 2.2 \pm 0.6$  °C,  $d=3.9$ ,  $p<0.001$ ; POST-MAIN SET:  $\Delta 3.2 \pm 0.5$  °C,  $d=6.1$ ,  $p<0.001$ ; POST-SESSION:  $\Delta 1.2 \pm 0.7$  °C,  $d=1.9$ ,  $p=0.006$ ).  $T_{sk}$  pre-session was less than post-session only in COLD conditions ( $\Delta -2.6 \pm 1.0$  °C,  $d=2.4$ ,  $p<0.001$ ) but increased in both conditions after the main set until post-session (COLD:  $\Delta 2.1 \pm 0.7$  °C,  $d=3.1$ ,  $p<0.001$ ; HOT:  $\Delta 2.0 \pm 0.8$  °C,  $d=2.5$ ,  $p<0.001$ ).



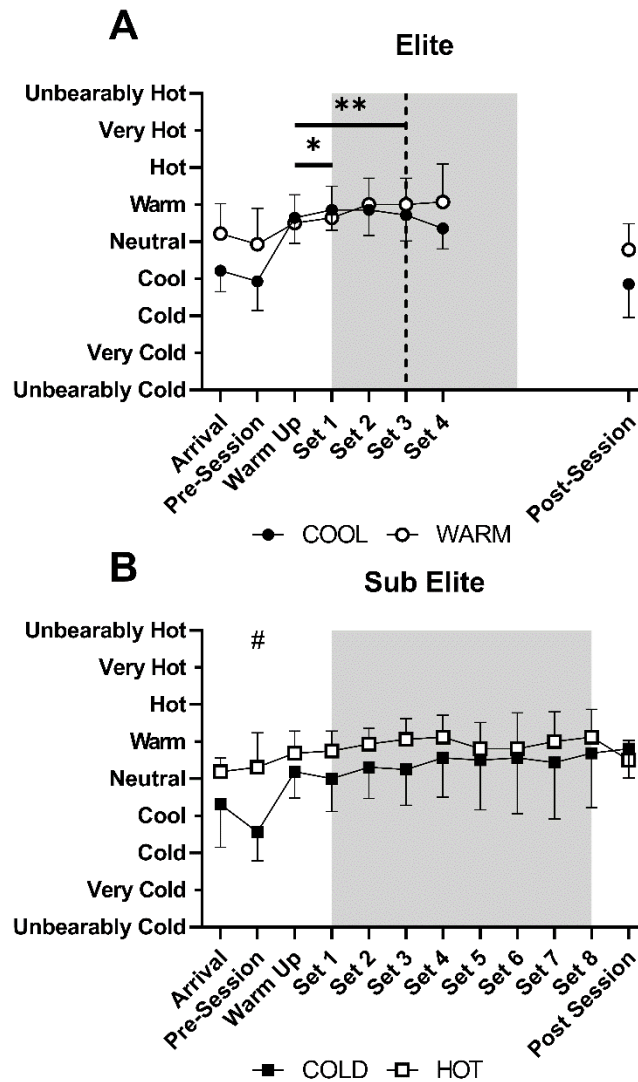
**Figure 2.4** Mean skin temperature during outdoor swim training for (A) elite swimmers undertaking a high intensity training session in COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions and (B) sub-elite swimmers during outdoor sprint training sessions in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions. Elite swimmers completed a total distance range 5.6-6.9 km with three  $\times$  100 m efforts whilst sub-elite swimmers completed a total distance range 4.6-7.5 km with eight  $\times$  50 m sprints. Data was recorded using a thermal imaging camera (A, B) and is presented as mean  $\pm$  standard deviation (A;  $n = 7$ , B;  $n = 8$ ). Data was analysed using a two-way repeated measures ANOVA (time  $\times$  trial) with Bonferroni post-hoc procedure for multiple comparisons. \*, significantly different to same timepoint in COLD ( $p < 0.001$ ), #, main effect of condition between COOL and WARM ( $p < 0.001$ ).

### 2.3.5 Thermal Sensation and Comfort

There was a significant interaction between trials for thermal sensation in elite and sub-elite swimmers (Elite:  $p = 0.032$ , Sub-Elite:  $p = 0.030$ , Figure 2.5). In the COOL trial, there was an increase in thermal sensation between arrival and warm up ( $\Delta 1.4 \pm 0.5$  AU,  $d = 2.7$ ), Set 1 ( $\Delta 1.6 \pm 0.5$  AU,  $d = 3.5$ ), Set 2 ( $\Delta 1.6 \pm 0.6$  AU,  $d = 2.6$ ) and Set 3 ( $\Delta 1.5 \pm 0.6$  AU,  $d = 2.6$ ), and also between pre-training and warm up ( $\Delta 1.7 \pm 0.9$  AU,  $d = 1.9$ ) and Set 1 ( $\Delta 1.9 \pm 0.9$  AU,  $d = 1.9$ ). However, there was no difference in thermal sensation for any time-points during the WARM trial. There were moderate effect sizes showing thermal sensation was higher in WARM compared to COOL upon arrival ( $\Delta 1.0 \pm 1.4$  AU,  $d = 0.72$ ), pre-training ( $\Delta 1.0 \pm 1.8$  AU,  $d = 0.6$ ) and post training ( $\Delta 0.9 \pm 1.6$  AU,  $d = 0.6$ ), but the differences were not statistically significant.

Sub-elite swimmers felt warmer in HOT conditions compared to COLD (HOT:  $4.8 \pm 0.3$  AU; COLD:  $4.2 \pm 0.6$  AU, Figure 2.5B), an effect that was most evident pre-session ( $\Delta 1.8 \pm 1.2$  AU,  $d = 1.5$ ,  $p = 0.014$ ). Thermal sensation did not change throughout the training session in the HOT trial whereas in COLD trial conditions thermal sensation increased compared to pre-session values (POST-WARM UP:  $\Delta 1.6 \pm 0.8$  AU,  $d = 2.1$ ,  $p = 0.043$ ; POST-SESSION:  $\Delta 2.3 \pm 0.6$  AU,  $d = 3.8$ ,  $p < 0.001$ ).

Despite elevated thermal comfort scores in the COOL compared to WARM trial, there was no significant difference or meaningful effect size for thermal comfort at any timepoint (Table 2.6). Mean thermal comfort (Table 2.6) was higher (main effect:  $p = 0.005$ ) during COLD ( $2.1 \pm 0.3$  AU) compared to HOT ( $1.6 \pm 0.3$  AU) trials and there was a main effect for time ( $p = 0.002$ ).



**Figure 2.5** Thermal sensation during outdoor high intensity training sessions for (A) elite swimmers in COOL ( $T_a = 15.5^\circ\text{C}$ , WBGT =  $14.7^\circ\text{C}$ ) and WARM ( $T_a = 23.4^\circ\text{C}$ , WBGT =  $23.0^\circ\text{C}$ ) conditions and sprint training sessions for (B) sub-elite swimmers in COLD ( $T_a = 11.8^\circ\text{C}$ , WBGT =  $10.3^\circ\text{C}$ ) and HOT ( $T_a = 26.3^\circ\text{C}$ , WBGT =  $27.0^\circ\text{C}$ ) conditions. Elite swimmers completed a total distance range of 5.0-5.9 km including four sets of three  $\times$  100 m efforts whilst sub-elite swimmers completed a session with total distance range 4.6-7.5 km including eight  $\times$  50 m sprint every 5 min during their main set. Both groups reported body temperature sensations on a 17-point scale (Young et al., 1987). Data are mean  $\pm$  standard deviation (elite;  $n = 7$ , sub-elite;  $n = 8$ ) in arbitrary units (AU) and were analysed using a two-way repeated measures ANOVA (time  $\times$  trial) with Bonferroni post-hoc procedure for multiple

comparisons (arbitrary units). Dashed line shows the prolonged rest period during training, while grey shading shows extended training for endurance swimmers ( $n = 2$ ). \* significantly different vs. Pre-training in COOL ( $p < 0.05$ ), \*\* significantly different vs. Arrival in COOL ( $p < 0.01$ ), # significantly different to same time-point in COLD.

**Table 2.6** Thermal comfort during outdoor high intensity training sessions for elite swimmers in COOL ( $T_a = 15.5^\circ\text{C}$ , WBGT =  $14.7^\circ\text{C}$ ) and WARM ( $T_a = 23.4^\circ\text{C}$ , WBGT  $23.0^\circ\text{C}$ ) conditions and sprint training sessions for sub-elite swimmers in COLD ( $T_a = 11.8^\circ\text{C}$ , WBGT  $10.3^\circ\text{C}$ ) and HOT ( $T_a = 26.3^\circ\text{C}$ , WBGT  $27.0^\circ\text{C}$ ) conditions. Elite swimmers completed a total distance range 5.6-6.9 km including three  $\times$  100 m efforts whilst sub-elite swimmers completed a total distance range 4.6-7.5 km with eight  $\times$  50 m sprints. Body temperature comfort was quantified using a 4-point scale (1=comfortable, 2=slightly uncomfortable, 3=uncomfortable, 4=very uncomfortable; Gagge et al., 1969). Data are mean  $\pm$  standard deviation in arbitrary units (elite;  $n = 7$ , sub-elite;  $n = 8$ ) and were analysed using a two-way repeated measures ANOVA (time  $\times$  trial) with Bonferroni post-hoc procedure for multiple comparisons (arbitrary units). In the elite group, for repetition 5 and repetition 6 only data from END ( $n = 4$ ) participants were collected.

Group	Trial	Arrival	Pre Training	Warm Up	Set								Post Training
					1	2	3	4	5	6	7	8	
Elite	COOL	1.7 (0.0)	1.7 (0.5)	1.4 (0.5)	1.4 (0.4)	1.6 (0.8)	1.6 (0.8)	1.4 (0.5)	1.5 (0.5)	1.5 (0.5)			1.7 (0.4)
	WARM	1.0 (0.5)	1.4 (0.7)	1.3 (0.6)	1.1 (0.6)	1.3 (0.9)	1.4 (0.9)	1.3 (0.9)	1.3 (1.0)	1.3 (1.0)			1.1 (0.8)
Sub-Elite	COLD	1.8 (0.7)	2.1 (0.6)	1.6 (0.8)	1.9 (0.4)	2.0 (0.0)	2.3 (0.5)	2.3 (0.5)	2.4 (0.5)	2.4 (0.5)	2.4 (0.5)	2.4 (0.5)	1.5 (0.8)
	HOT	1.0 (0.0)	1.4 (0.7)	1.5 (0.5)	1.3 (0.5)	1.8 (0.5)	1.9 (0.6)	1.9 (0.6)	1.9 (0.6)	2.0 (0.5)	1.9 (0.6)	1.9 (0.6)	1.4 (0.5)

### 2.3.6 Fluid Balance

There was no significant difference in waking urine specific gravity nor total fluid consumption between trials (USG; Elite:  $p = 0.64$ , Sub-elite:  $p = 0.95$ , TFC; Elite:  $p = 0.92$ , Sub-elite:  $p = 0.38$ , Table 2.7). WBSR and WBSL was not significantly different between COOL and WARM trials despite a small reduction in WBSL in the COOL trial compared to WARM ( $-0.14\text{L} \pm 0.6$ ,  $d = 0.23$ ). There was a large increase in WBSL in HOT compared to COLD conditions ( $\Delta 0.35 \pm 0.39\text{ L}$ ,  $d = 0.91$ ,  $p = 0.04$ ) and an associated increase in WBSR ( $\Delta 0.17 \pm 0.20\text{ L}\cdot\text{h}^{-1}$ ,  $d = 0.95$ ,  $p = 0.04$ ).

**Table 2.7** Urine specific gravity, fluid consumption, whole body sweat loss and sweat rate of elite swimmers during outdoor high intensity training sessions in COOL ( $T_a$  15.5°C, WBGT 14.7°C) and WARM ( $T_a$  23.4°C, WBGT 23.0°C) conditions and sub elite swimmers sprint training sessions in COLD ( $T_a$  11.8°C, WBGT 10.3°C) and HOT ( $T_a$  26.3°C, WBGT 27.0°C) conditions. Elite swimmers completed a training session with total distance range 5.6-6.9 km with three  $\times$  100 m efforts whilst sub elite swimmers completed a session with a total distance range 4.6-7.5 km with eight  $\times$  50 m sprints. Data was recorded using a refractometer and weighing scale. Data are presented as mean ( $\pm$  standard deviation) and were analysed using paired Student's t-tests for urine specific gravity (elite;  $n = 7$ , sub elite;  $n = 8$ ), fluid consumption (elite;  $n = 7$ , sub-elite;  $n = 8$ ), whole body sweat loss (elite;  $n = 6$ , sub-elite;  $n = 8$ ) and whole body sweat rate (elite;  $n = 6$ , sub-elite;  $n = 8$ ).

	Elite		Sub-elite		Elite		Sub-elite	
	COOL	WARM	COLD	HOT	p-value	Cohen's $d$	p-value	Cohen's $d$
Urine Specific Gravity	1.023 (0.003)	1.023 (0.004)	1.022 (0.005)	1.022 (0.004)	0.64	0.19	0.95	-0.03
Total Fluid Consumption (L)	0.41 (0.42)	0.44 (0.42)	0.46 (0.32)	0.35 (0.31)	0.92	0.04	0.38	-0.33
Sweat Loss (L)	0.67 (0.29)	0.53 (0.74)	0.42 (0.32) <sup>a</sup>	0.77 (0.45)	0.60	0.23	0.04	0.91
Sweat Rate (L/h)	0.33 (0.16)	0.27 (0.37)	0.21 (0.16) <sup>a</sup>	0.39 (0.22)	0.69	0.18	0.04	0.95

<sup>a</sup> , significantly lower compared to HOT ( $p < 0.05$ ).



## 2.4 Discussion

The aim of this study was to determine the effect of environmental conditions during outdoor training on thermal physiology, thermal perceptions, and work performed in highly trained swimmers. These data show divergent environmental conditions can alter skin temperature and thermal sensation of swimmers training outdoors with no associated changes in performance between conditions. Core temperature and thermal comfort were unchanged in warm but there was increased thermal discomfort in cold compared to hot conditions.

A major finding of this study was that skin temperature was different with contrasting wet bulb globe temperatures during the training sessions, despite water temperatures that were effectively interchangeable. As might be expected, the skin temperature of athletes upon arrival for training appeared to reflect the  $T_a$  and was higher in warm conditions, and skin temperature decreased during training which is likely attributable to the heat conduction properties of water. Importantly, the absolute difference in  $T_{sk}$  between conditions were larger than previous studies showing faster 100 m freestyle times were associated with warmer pre-time trial  $T_{sk}$  (McGowan et al., 2017; McGowan, Thompson, Pyne, Raglin & Rattray, 2015). However, the extent that the differences in  $T_{sk}$  in this study affected performance is difficult to ascertain because repeated interruption of training to obtain more frequent  $T_{sk}$  data was a limitation of the study design in the applied sport setting. Additionally, there is no viable technology to determine  $T_{sk}$  whilst swimming. During the time between exiting the pool and image capture, skin temperature likely increased in a logarithmic manner (Jimenez-Perez, Gil-Calvo, Vardasca, Fernandes, Vilas-Boas, 2021) and may not be indicative of  $T_{sk}$  during swimming alone. Nonetheless, the difference in skin temperature between trials upon arrival was largely maintained throughout the training session indicating the potential for the  $T_a$  to effect thermal sensation and/or performance, at least during recovery between swimming sets.

In contrast, there were increases in core temperature during swim training but no effect of the different environmental conditions on core temperature. Our findings are in agreement with previous studies showing modest increases in core temperature (0.5-0.7 °C) during swimming bouts (26-27°C water temperature) of 20 min at ~50-70% maximal velocity, maximal swimming efforts, and 60 min at ~68% maximal oxygen uptake (Costill, Cahill, & Eddy, 1967; Nadel, Holmer, Bergh, Astrand, & Stolwijk, 1974; Holmér & Bergh, 1974; Galbo et al., 1979). Taken together, the data show that the thermoregulatory challenge to core temperature during swimming is modest, even with warm environmental conditions, and the concomitant decrease in skin temperature in the present study also indicates a greater temperature gradient for heat transfer from the body's core to the skin compared to exercise in terrestrial conditions (Cuddy et al., 2014).

Skin temperature and thermal sensation are purported to be closely associated in various ambient environments (Schlader, Simmons, Stannard, & Mündel, 2011b). Moreover, thermoreceptors in the skin and central nervous system generate afferent signals to the hypothalamus where thermoregulation is controlled (Filingeri, 2016) to link skin temperature and individual psychophysiological sensitivity to temperature variance (Cheung, 2010). The data in the present study supports such a contention, given higher skin temperature upon arrival for training during warm/hot conditions was associated with higher ratings of thermal sensation. Previous studies have reported increased discomfort during passive rest in cold compared to thermoneutral and warm conditions, and that the thermal discomfort has the capacity to promote changes in behaviour to maintain body temperature in cold conditions (Gagge, Stolwijk, & Hardy, 1967). In contrast, in thermoneutral or warm conditions, increased vascular conductance and the relative efficiency of body cooling mechanisms does not typically require significant behavioural change to maintain resting heat balance (Gagge et al., 1967). However, *during* training thermal sensation was similar between trials and it may be

that the high intensity exercise within the swimming sessions equalized the perception of thermal sensation regardless of the ambient temperature. This effect was also associated with no meaningful difference in thermal comfort between trials despite swimmers tending to have slightly higher thermal discomfort in cool/cold conditions, which is in contrast to terrestrial exercise where higher rating of thermal discomfort is associated with higher ratings of thermal sensation and elevated skin temperature (Schlader et al., 2011b). This suggests that the thermal sensation and comfort responses during swimming may parallel with those observed during passive rest rather than exercise in terrestrial environments.

Athletic success in competition is typically defined by very small margins, where differences are often measured in tenths of a second (Pyne, Trewin & Hopkins, 2004). Moreover, a key factor contributing to competition performance is the cumulative adaptive response to repeated bouts of training, so the quality of training becomes critical to success. Notably, time to completion for the high intensity and sprint repetitions during swim training in the present study was not different between warm/hot and cool/cold trials despite the observation of small-to-moderate effects (1.7-3.3%) of warm/hot conditions which may be meaningful for elite swimmers. Elite swimming performance varies by ~1% between competitions during a season and performance tends to improve as the season progresses (Pyne et al., 2004). The performance effect in our study was often greater than this typical variation but given the data was collected during different phases of the periodized training plan the possibility exists that changes in adaptive state may have affected training performance. Precision in recording swim times and the requirement for self-pacing may also add technical error to the measurement.

Variance in sprint performance proportional to ambient temperature has been observed in cycling (Girard et al., 2015) and running (Guy et al., 2015). Moreover, higher ambient temperature can enhance short-term sprint performance compared to cooler conditions if

increased muscle temperature with short bouts of exercise in the heat is not offset by cardiovascular and metabolic strain as a result of heat stress (Girard et al., 2015). The measurement of heart rate in the current study would have provided insight into whether the different environmental conditions affected cardiovascular strain during training for elite swimmers. Additionally, skin temperature is purported to be the predominant determinant of endurance capacity (Sawka et al., 2012) and performance (Racinais et al., 2021) during terrestrial exercise. It may be that the differences in skin temperature and thermal sensation observed in the current study were not large enough to elicit a consistent performance effect during swimming or that the methods used lacked the sensitivity to reliably observe changes between conditions. Technical error of thermal imaging data was minimized by employing “best practice” protocols described by Moreira et al. (2017) but thermal imaging has greater variance in recording skin temperature compared with conductive thermocouples (Bach et al., 2015). Nonetheless, the protocol for capturing and quantifying images was consistent and the temporal proximity after leaving water was closely replicated between trials to provide reasonable quantification of skin temperature in an applied sport science setting. Alternately, data from the many studies employing terrestrial exercise under divergent thermal conditions may not be readily transferable to aquatic environments. It is unclear whether similar findings would be evident in swimming sets with longer duration repetitions or with shorter recovery periods and if a controlled laboratory approach could be used to determine the effects of a range of ambient temperatures on repeat sprint performance for swimmers. Given this is the first study to characterize the effect of environmental conditions on thermoregulation and swimming performance during outdoor pool swimming in highly trained swimmers it is clear more research is needed to determine whether the findings can be replicated and/or are generalizable to different training contexts.

In summary, this data is the first to show the effect of the environment on thermal physiology and perception during outdoor swim training in highly trained, elite athletes. The study found that skin temperature and thermal sensation vary dependent on ambient temperature despite consistent water temperature. However, the quality of training was unchanged during hot/warm compared to cold/cool seasonal conditions. Therefore, coaches and highly trained swimmers training outdoors can be confident that any pre-session skin temperature and perceptual differences in response to seasonal or locational changes in environmental conditions is likely to have a minor effect on training performance.

---

## **Chapter 3**

Effect of acetaminophen on steady state and time trial  
cycling performance in endurance trained triathletes  
in hot and humid conditions

---

### 3.1 Abstract

The ergogenic effect of various pre- and per-cooling strategies during endurance exercise in hot and humid environmental conditions has been extensively investigated but the effect of acetaminophen (ACT, also known as paracetamol) on endurance performance in trained individuals in these conditions is unknown. The aim of this study was to determine the effect of ACT on physiological and perceptual variables during steady state and time trial cycling performance of trained triathletes in hot and humid conditions. In a randomized, double-blind crossover design, eleven triathletes completed ~60 min steady state cycling at 63% peak power output followed by a time trial ( $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{body mass}^{-1}$ ) in hot and humid conditions ( $\sim 30^{\circ}\text{C}$ ,  $\sim 69\%$  relative humidity) 90 min after consuming either  $20 \text{ mg} \cdot \text{kg body mass}^{-1}$  ACT or a colour matched placebo (PLA). Time trial completion time, gastrointestinal temperature, skin temperature, thermal sensation, thermal comfort, rating of perceived exertion and fluid balance were recorded throughout each session. Time trial completion time was greater in the ACT condition, however this difference was not statistically significant despite a moderate effect for poorer performance compared to PLA (64.6s, CI = -11.08 to 140.3s,  $d=0.57$ ,  $p=0.086$ ). There were no differences in gastrointestinal and skin temperature, thermal sensation and comfort, or fluid balance between conditions. In conclusion, the antipyretic and analgesic effects typically associated with ACT were not apparent in trained triathletes and existing pre- and per-cooling strategies appear to be more appropriate for endurance triathlon performance in the heat.

### 3.2 Introduction

It is well known that hot and humid environmental conditions reduce endurance exercise performance in trained individuals (Galloway & Maughan, 1997; Peiffer & Abbiss, 2011). The impaired performance is typically related to a combination of factors including increased cardiovascular strain and decreased neural drive, as well as dehydration during prolonged exercise bouts (Trangmar & González-Alonso, 2019). Accordingly, numerous studies have been undertaken to determine the efficacy of various cooling strategies to mitigate the detrimental effects of hot conditions on human performance. The methods of cooling can be categorized as interventions before (pre-cooling) or during (per-cooling) exercise and have been shown to improve performance of endurance events in the heat (Bongers et al., 2015; Racinais et al., 2020).

Effective pre- and per-cooling techniques generally aim to reduce core temperature and/or skin temperature, decreasing the net heat storage in the body and increasing the magnitude of heat production required to upregulate autonomic thermoregulatory mechanisms (Ross et al., 2011). Common methods of pre-cooling for elite endurance competition include cold water immersion and ice slurry ingestion while ice vests and ice towels are commonly used as per-cooling methods (Bongers et al., 2017; Ross et al., 2013). However, methods such as cold water immersion and ice slushy ingestion prior to endurance exercise may delay the sweat response, and any physiological effect on core and skin temperature is transient (Choo et al., 2019; Ross et al., 2013). Implementing pre-cooling methods often presents logistical challenges in the field and the transient physiological impact also dictates that the timing and proximity to exercise is critical to achieve a beneficial effect. Clearly, there are practical limitations to specific cooling methods and pharmaceutical compounds may represent alternate, less onerous ergogenic aids for elite endurance athletes participating in major events in hot conditions. Acetaminophen is an ergogenic aid that has been associated with increased cycling performance in trained and



recreationally active humans but its potential to improve endurance performance in hot conditions is unknown (Mauger et al., 2010; Mauger et al., 2014).

Acetaminophen, also known as paracetamol, is a widely used medication with antipyretic and analgesic properties and is commonly used to reduce fever and pain during illness (Anderson, 2008). For example, an acetaminophen dose of 20 mg·kg body mass<sup>-1</sup> (BM) has been shown to reduce core temperature in resting, afebrile individuals compared to placebo (Foster, Mauger, Govus, Hewson, & Taylor, 2017; Foster, Mauger, Thomasson, White, & Taylor, 2016). Whether similar effects are evident when acetaminophen is ingested for pre- and per-cooling in endurance exercise has not been established. Plasma acetaminophen concentration has been shown to remain elevated for ~2 h post-ingestion (Foster et al., 2016) and a 17% increase in short duration, high intensity exercise (time to exhaustion trial) performance in hot conditions (~30°C, ~50% RH) has been reported (Mauger et al., 2014). Conversely, studies have also shown only modest physiological or ergogenic effects of acetaminophen during 30-60 min moderate intensity endurance exercise bouts (Coombs et al., 2015; Veltmeijer et al., 2017). Therefore, while there may be an apparent ergogenic effect of acetaminophen it is unclear whether acetaminophen ingestion would improve the performance of trained endurance athletes undertaking a high intensity cycling bout in hot and humid conditions. The aim of the present study was to determine the effect of acetaminophen ingestion on cycling time-trial performance in endurance trained athletes in hot and humid environmental conditions. The hypothesis was that acetaminophen ingestion would be associated with improved endurance cycling time-trial performance in the heat concomitant with a decrease in gastrointestinal temperature and thermal sensation.

### 3.3 Methods

#### 3.3.1 Participants

Thirteen endurance trained triathletes (de Pauw et al., 2013) volunteered to take part in the study (Table 3.1). Due to injury and illness,  $n = 2$  did not complete experimental trials. Informed written consent was obtained from all athletes prior to participation in the study and ethical approval was granted by the Bond University Human Research Ethics Committee (GW02854).

**Table 3.1** Participant characteristics.

Males/Females	9 / 4
Age (years)	$29.2 \pm 8.4$
Height (cm)	$175.3 \pm 7.6$
Body Mass (kg)	$67.2 \pm 9.0$
$\text{VO}_{2\text{peak}}$ ( $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	$64.5 \pm 8.5$
Peak Power Output (Watts)	$338.3 \pm 61.6$
Lean Muscle Mass (kg)	$54.9 \pm 8.8$
Body Fat (%)	$15.4 \pm 3.7$
Body Surface Area ( $\text{m}^2$ )	$1.8 \pm 0.2$

Data are mean  $\pm$  standard deviation.  $\text{VO}_{2\text{peak}}$ , peak oxygen uptake.

### 3.3.2 Experimental Overview

A within-participant placebo controlled randomised double-blind crossover study design was employed with trials undertaken after either oral ingestion of acetaminophen or a placebo (Figure 3.1). Participants completed a 60 min steady state cycling bout followed by a 7 kJ·kg BM<sup>-1</sup> time trial in hot and humid conditions (~30°C, ~70% RH, wind speed ~1.5 m·s<sup>-1</sup>, ~27 °C WBGT) during each condition. Participants were matched for VO<sub>2peak</sub> then a coin toss was used to allocate the experimental order.

### 3.3.3 Preliminary Testing

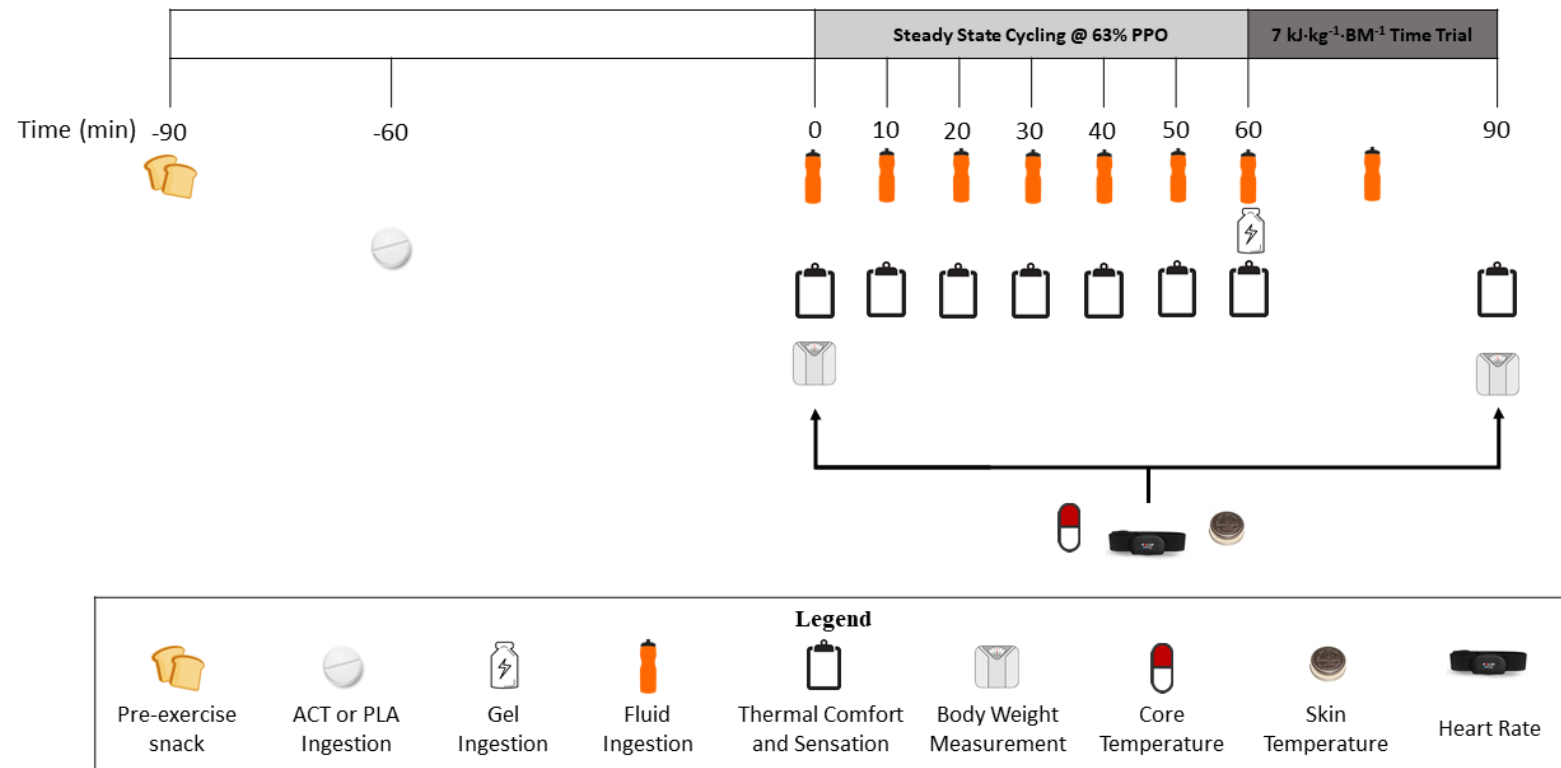
Prior to commencing experimental trials participant anthropometric assessment was undertaken. Body mass was determined using electronic scales (WM204, Wedderburn, Australia) and height using a wall-mounted stadiometer (Harpenden stadiometer, Holtain Limited, UK). Dual energy X-ray absorptiometry was used to determine body composition while air displacement plethysmography was used to quantify body volume and surface area.

Participants arrived at the laboratory after an overnight fast and voided their bladder before undergoing a dual energy X-ray absorptiometry (DEXA) scan (Lunar Prodigy DXA machine, GE Healthcare, USA). The scan was performed by a licensed practitioner using methods described previously (Nana et al., 2015). Briefly, participants clothed in their cycling bib lay in a supine position, palms flat and separated from the torso with feet together. Post-scan segmentation was identified using the proprietary software (GE encore 2016 software, GE Healthcare, Madison, WI, USA). Data was expressed relative to body mass.

Air displacement plethysmography was performed using a BODPOD® (Cosmed, USA) according to the manufacturer's instructions. Briefly, participants were clothed in their cycling bib and wore a swim-cap during the scan. Air-displacement plethysmography was used to

determine body volume (L) with body density being calculated using the equation of Siri (1956) and lung volume predicted using the equation of Crapo et al. (1982).

Participants were provided with a pre-exercise snack before beginning a cycling familiarisation trial. Subsequently, they completed a 10 min warm-up at self-selected intensity followed by a maximal incremental test to volitional fatigue as described previously (Hawley & Noakes, 1992). Briefly, participants completed a step-test consisting of 150 s stages beginning at  $3.33 \text{ W} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  with an initial increase of 50 W and increasing 25 W thereafter until fatigue or cadence reduced by greater than 10 rpm. Breath-by-breath respiratory gas data was averaged as 30 s epochs throughout the test via metabolic cart (Quark C-PET; Cosmed, Italy). Calibration was determined using a 3-L syringe and  $\text{O}_2/\text{CO}_2$  reference gases (16%  $\text{O}_2$ , 4%  $\text{CO}_2$ ; Air Liquide Healthcare, Healthcare Corporation America, USA). Peak oxygen uptake ( $\text{VO}_{2\text{peak}}$ ) was defined as the highest oxygen uptake attained during two consecutive 30 second sampling periods whilst peak power output (PPO) was calculated using time spent at the final non-completed workload plus the last fully completed work load (Hawley & Noakes, 1992). Finally, after a ~5 min self-selected cooldown and ~5 min passive rest, participants completed a familiarisation session which included a 10 min steady state ride at 63% peak power output followed by a short passive recovery (2 min), and thereafter undertook the same  $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  performance time trial used in the experimental trial (described subsequently) but in temperate conditions ( $23.4 \pm 1.2^\circ\text{C}$ ,  $63.1 \pm 7.6\% \text{ RH}$ ). Participants were familiarised with perceptual scales during the 10 min steady state cycling bout. All participants were endurance trained athletes experienced in undertaking high intensity self-paced cycling in competition, and the preliminary trial ensured that participants were familiar with the laboratory procedures and requirements of the performance test.



**Figure 3.1** Overview of an experimental trial (n=11 participants) showing the steady state cycling and time trial, and timeline of dependent variable data collection to determine physiological and perceptual responses. Arrows depict timepoints where data was collected for each variable. The white box denotes the pre-testing phase, the light grey steady state cycling and dark grey the cycling time trial. PPO, peak power out; BM, body mass.

### 3.3.4 Dietary Standardisation

Upon arrival for experimental trials, participants provided a urine sample collected mid-stream upon waking which was analysed using a refractometer (PAL-10S, Atago, Japan) to determine hydration status via urine specific gravity (USG). A standardised diet ( $220 \text{ kJ} \cdot \text{kg BM}^{-1}$ ;  $8 \text{ g CHO} \cdot \text{kg BM}^{-1}$ ) was prescribed for the 24 h prior to trials. Participants arrived fasted and were provided with a pre-exercise snack ( $40 \text{ kJ} \cdot \text{kg BM}^{-1}$ ;  $2 \text{ g CHO} \cdot \text{kg BM}^{-1}$ ) 90 min prior to commencing exercise. During steady state cycling  $5 \text{ mL H}_2\text{O} \cdot \text{kg BM}^{-1}$  was provided every 20 min to be consumed within 5 min of presentation. During the short period between steady state cycling and the time trial,  $3 \text{ mL H}_2\text{O} \cdot \text{kg BM}^{-1}$  and a carbohydrate energy gel (Koda energy gel<sup>TM</sup> –  $495 \text{ kJ}$ ;  $30 \text{ g CHO}$ ) was ingested. Participants were permitted to drink water ad-libitum during the first time trial with the volume of water matched during the subsequent trial.

### 3.3.5 Environmental Conditions

Each trial was undertaken in a room/structure where environmental conditions were maintained at  $\sim 30^\circ\text{C}$ ,  $\sim 70\%$  RH (Acetaminophen trial:  $T_a = 29.9 \pm 0.7^\circ\text{C}$ ,  $\text{RH} = 68.7 \pm 2.7\%$ ,  $\text{AH} = 21.3 \pm 0.5 \text{ g} \cdot \text{m}^3$ ,  $\text{WBGT} = 26.6 \pm 0.3^\circ\text{C}$ ; Placebo trial:  $T_a = 29.7 \pm 0.7^\circ\text{C}$ ,  $\text{RH} = 68.7 \pm 2.8\%$ ,  $\text{AH} = 21.3 \pm 0.5 \text{ g} \cdot \text{m}^3$ ,  $\text{WBGT} = 26.7 \pm 0.2^\circ\text{C}$ ) and recorded by dual Kestrel 5400 monitors (Kestrel Instruments, USA). Facing wind speed  $\sim 1.5 \text{ m} \cdot \text{s}^{-1}$  was facilitated using a fan and WBGT indoors calculated using the Bernard method (Bernard, 1999).

### 3.3.6 Steady State and Time Trial Cycling

All experimental trials were undertaken in the morning (0530-1030) at the same time for each participant. Prior to the exercise bout (60 min) participants ingested gelatine capsules containing either  $20 \text{ mg} \cdot \text{kg BM}^{-1}$  acetaminophen (ACT) or a colour-matched placebo (cornflour; PLA). Participants completed both steady state and time trial cycling on an

electromagnetically braked ergometer (Lode Instruments; Groningen, The Netherlands) which was set up to replicate participants' individual bicycle settings. The trial replicated methodology used in previous research (Cox et al., 2002) with total duration of exercise (~ 90 min) similar to the cycling and running legs of an Olympic distance triathlon separated by a transition period. Participants had 5 min to progress mechanical work to the required 63% peak power output (~70%  $\text{VO}_{2\text{peak}}$ ) which they then maintained for 55 min. The steady state cycling was followed by a short passive recovery period (2 min). The time trial was undertaken using a previously derived linear factor that was calculated to permit each participant to complete the exercise bout at a preferred cadence equivalent to ~85% of peak power output. Participants then commenced the  $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  time trial and time to completion was recorded using a handheld stopwatch. Participants received no feedback during the time trial except notification of each 10% of work completed and no verbal encouragement was provided during the time trial.

### **3.3.7 Gastrointestinal and Skin Temperature**

Gastrointestinal temperature ( $T_{\text{gi}}$ ) was recorded as a non-invasive, valid and reliable measure of core temperature (Bongers et al., 2018). Data were recorded at 30 s intervals which were subsequently converted to 60 s epochs for analysis. Participants ingested the thermistor pill ~9-10 h prior to arrival for an experimental trial (e-Celsius Performance; Bodycap, France). Skin temperature ( $T_{\text{sk}}$ ) was determined using a thermochron attached to the skin (iButton; Maxim Integrated, USA) with medical tape (Fixomull, BSN Medical, Germany) as per criterion protocols. Thermochrons were placed on the back (infraspinal), chest (between the 5th and 6th rib), mid-bicep, mid-thigh and medial mid-calf. Mean skin temperature was calculated using the unweighted mean of sites on the back, bicep, thigh, and calf (Mitchell & Wyndham, 1969).

### **3.3.8 Heart Rate**

Heart rate (HR) was recorded at a frequency of 1 Hz by telemetry (Polar H10; Kempele, Finland) and was recorded using a proprietary app (Polar Beat; Polar Electro, Kempele, Finland). The data was saved to a cloud-based software (Polar Flow; Polar Electro, Kempele, Finland) before being exported for analysis.



### 3.3.9 Perceptual Measures

Perceived thermal comfort on a 4-point Likert scale (1 comfortable, 4 uncomfortable; Gagge et al., 1969), perceived thermal sensation on a 17-point Likert scale (0.0 unbearably cold, 4.0 neutral, 8.0 unbearably hot; Young et al., 1987) and rating of perceived exertion (6-20 RPE; Borg et al., 1982) were assessed verbally after reference to the visual scale. Data was obtained immediately before the steady state cycling, every 10 min during steady state cycling and immediately following time trial completion.

### 3.3.10 Fluid Balance

Participants towel-dried and were weighed nude to determine body mass immediately prior to and immediately after exposure to the hot environment (WM204; Wedderburn, Australia). If participants voided their bladder during the 2 min between steady state riding and the time trial, they were weighed before and after to record excreted fluid loss. Participants' drink bottles were weighed using portable scales (KD-192, Tanita, Japan) before and after the trial to determine total fluid consumption. Whole body sweat loss (WBSL) was calculated using the following formula:

$$\text{WBSL (L)} = (\text{Body Mass PRE (kg)} - \text{Body Mass POST (kg)}) + \text{Total Fluid Consumption (L)} - \text{Urine Loss (L)} \quad \text{Equation 3.1}$$

Whole body sweat rate (WBSR) was determined using the following equation:

$$\text{WBSR} \left( \frac{\text{L}}{\text{h}} \right) = \frac{\text{WBSL (L)}}{\text{Exercise Duration (h)}} \quad \text{Equation 3.2}$$

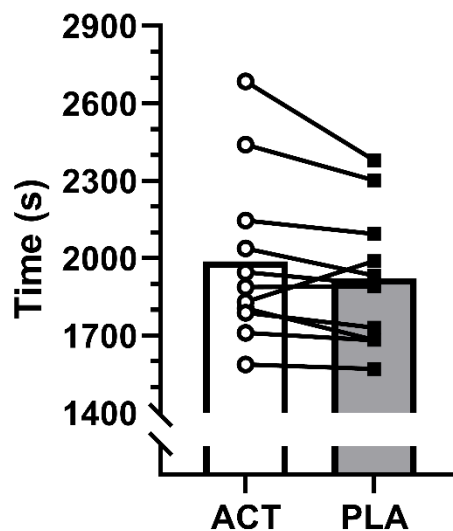
### 3.3.11 Statistical Analyses

Physiological and perceptual measures were analysed between conditions using a repeated-measures (condition [placebo, acetaminophen]  $\times$  time [0-60 min, 10-100% completion]) analysis of variance (ANOVA). Sphericity was tested using Mauchly's test and when sphericity was violated a Greenhouse-Geisser correction was used. When significant interactions were observed, post-hoc pairwise comparisons were conducted using a Bonferroni correction. Time to completion of the time trial, fluid balance and USG was analysed using a paired t-test. Effect sizes were calculated using Cohen's  $d$  with thresholds for small (0.2), moderate (0.5) and large (0.8) interpreted according to Cohen (2013). Statistical analyses were conducted using GraphPad Prism (version 8.4.2, GraphPad Software Inc, USA). Data are mean  $\pm$  standard deviation and statistical significance was set at  $P < 0.05$ .

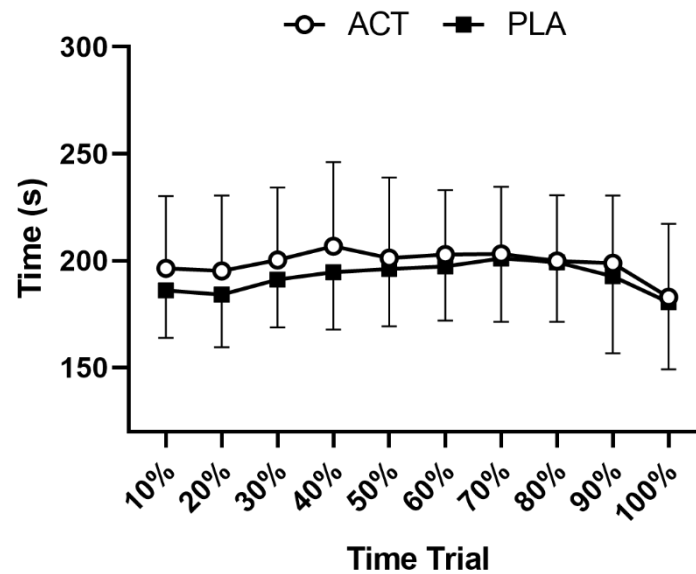
## 3.4 Results

### 3.4.1 Performance

There was a moderate effect for slower time to completion of the cycling time trial in the ACT compared to the PLA condition, but this mean difference did not reach statistical significance ( $64.6 \pm 112.7$  s,  $d = 0.57$ ,  $p = 0.086$ ; Figure 3.2). Additionally, there were small effects for time to completion during the acetaminophen time trial at 10% ( $10.7 \pm 40.4$  s,  $d = 0.26$ ), 20% ( $11.1 \pm 43.0$  s,  $d = 0.26$ ), 30% ( $9.1 \pm 40.6$  s,  $d = 0.22$ ) and 40% work completed ( $12.2 \pm 47.6$  s,  $d = 0.26$ , all  $p > 0.05$ ; Figure 3.3). No order effect between conditions was evident ( $p = 0.382$ ).



**Figure 3.2** Time to completion of a  $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  time trial in hot and humid conditions undertaken by endurance trained triathletes ( $n = 11$ ) after consuming a  $20 \text{ mg} \cdot \text{kg} \text{ BM}^{-1}$  dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\%$  RH) or placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\%$  RH). Participants completed the time trial after cycling for  $\sim 60$  min in hot and humid conditions at 63% of their previously determined peak power output. Data are mean  $\pm$  standard deviation and were analysed using a paired t-test with alpha set at  $P < 0.05$ .



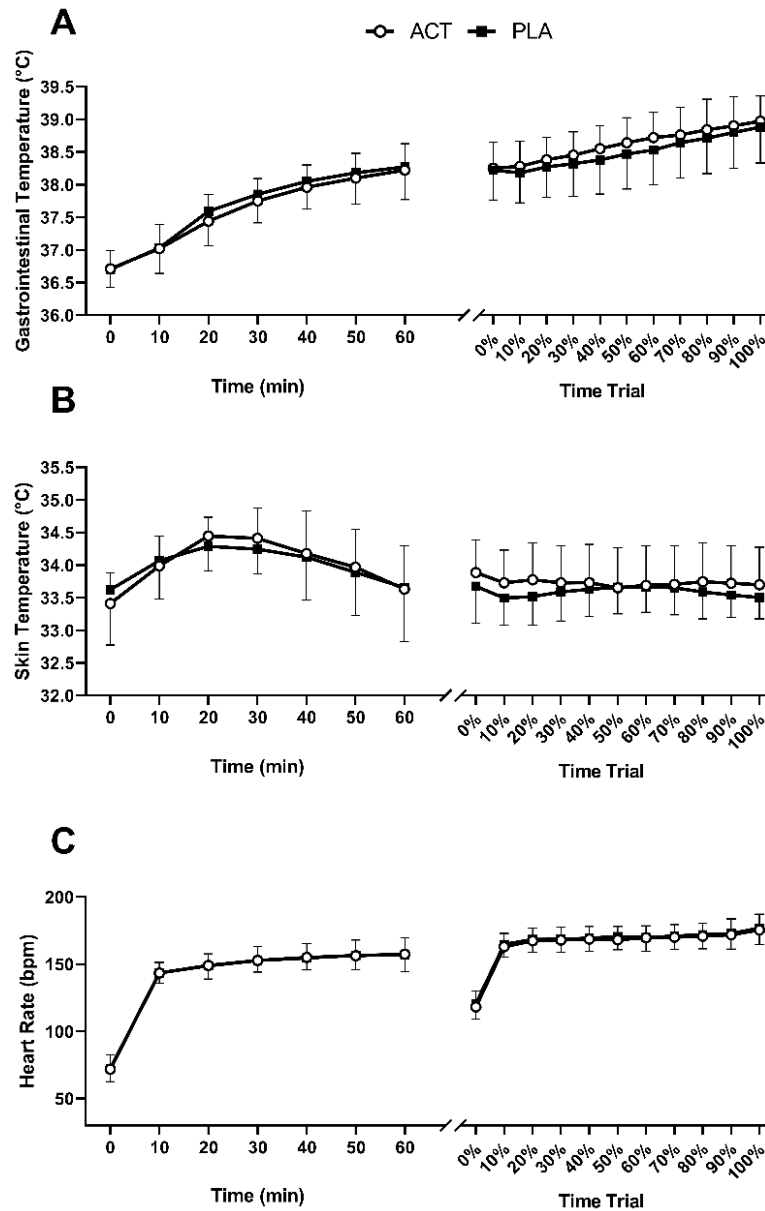
**Figure 3.3** Time to completion for each 10% of work during a cycling time trial ( $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$ ) in hot and humid conditions undertaken by endurance trained triathletes ( $n = 11$ ) after consuming  $20 \text{ mg} \cdot \text{kg} \text{ BM}^{-1}$  dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) and placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). Participants completed the time-trial after cycling for  $\sim 60$  min at 63% of their predetermined peak power output. Data are mean  $\pm$  standard deviation and were analysed using two-way repeated measures ANOVA (condition  $\times$  time) with post-hoc Bonferroni procedure for multiple comparisons ( $P < 0.05$ ).

### 3.4.2 Gastrointestinal Temperature, Skin Temperature and Heart Rate

ACT had no effect on  $T_{gi}$  during both steady state cycling (interaction effect:  $p = 0.938$ , main effect:  $0.572$ ) and the cycling time trial (interaction effect:  $0.872$ , main effect:  $0.542$ ) compared with PLA. There was a main effect of time ( $p < 0.001$ ; Figure 3.4A) on core temperature with a large increase observed during steady state cycling (ACT:  $\Delta 1.5 \pm 0.4^{\circ}\text{C}$ , PLA:  $\Delta 1.6 \pm 0.4^{\circ}\text{C}$ ) and the time trial (ACT:  $\Delta 0.7 \pm 0.3^{\circ}\text{C}$ , PLA:  $\Delta 0.7 \pm 0.3^{\circ}\text{C}$ ). Gastrointestinal temperature was similar between conditions at the completion of steady state cycling (ACT:  $38.2 \pm 0.5^{\circ}\text{C}$ , PLA:  $38.3 \pm 0.4^{\circ}\text{C}$ ) and following the time trial (ACT:  $38.9^{\circ}\text{C} \pm 0.5$ , PLA:  $39.0^{\circ}\text{C} \pm 0.4$ ).

Mean  $T_{sk}$  was not different in the ACT compared to the PLA condition at any timepoint (interaction effect:  $p = 0.594$ , main effect:  $0.643$ ). Mean  $T_{sk}$  fluctuated in both conditions, increasing during the early period (20 min) of steady state cycling (ACT:  $\Delta 1.0 \pm 0.6^{\circ}\text{C}$ ,  $d = 1.0$ ,  $p = 0.216$ ; PLA:  $\Delta 0.7 \pm 0.5^{\circ}\text{C}$ ,  $d = 2.1$ ,  $p = 0.523$ ) before decreasing until the completion of the steady state bout (ACT:  $33.6 \pm 0.8^{\circ}\text{C}$ ,  $\Delta -0.8 \pm 0.5^{\circ}\text{C}$ ,  $d = -1.5$ ,  $p = 0.302$ ; PLA:  $33.7 \pm 0.6^{\circ}\text{C}$ ,  $\Delta -0.6^{\circ}\text{C} \pm 0.4$ ,  $d = -1.5$ ,  $p = 0.266$ ; Figure 3.4B). There was a moderate effect for the decrease in  $T_{sk}$  during the ACT trial ( $\Delta -0.3 \pm 0.5^{\circ}\text{C}$ ,  $d = -0.57$ ) whilst in the PLA trial it was a small effect ( $\Delta -0.2 \pm 0.9^{\circ}\text{C}$ ,  $d = -0.26$ ). Direct comparisons at work completed milestones during time trials showed small effects for higher  $T_{sk}$  at the commencement, and after 10% and 20% ( $\Delta 0.3^{\circ}\text{C}$  to  $0.37^{\circ}\text{C}$ ,  $d = 0.28$  to  $0.36$ ), as well as 80%, 90% and upon completion of the ACT time trial ( $\Delta 0.22^{\circ}\text{C}$  to  $0.28^{\circ}\text{C}$ ,  $d = 0.22$  to  $0.28$ ), although none of the differences were statistically significant.

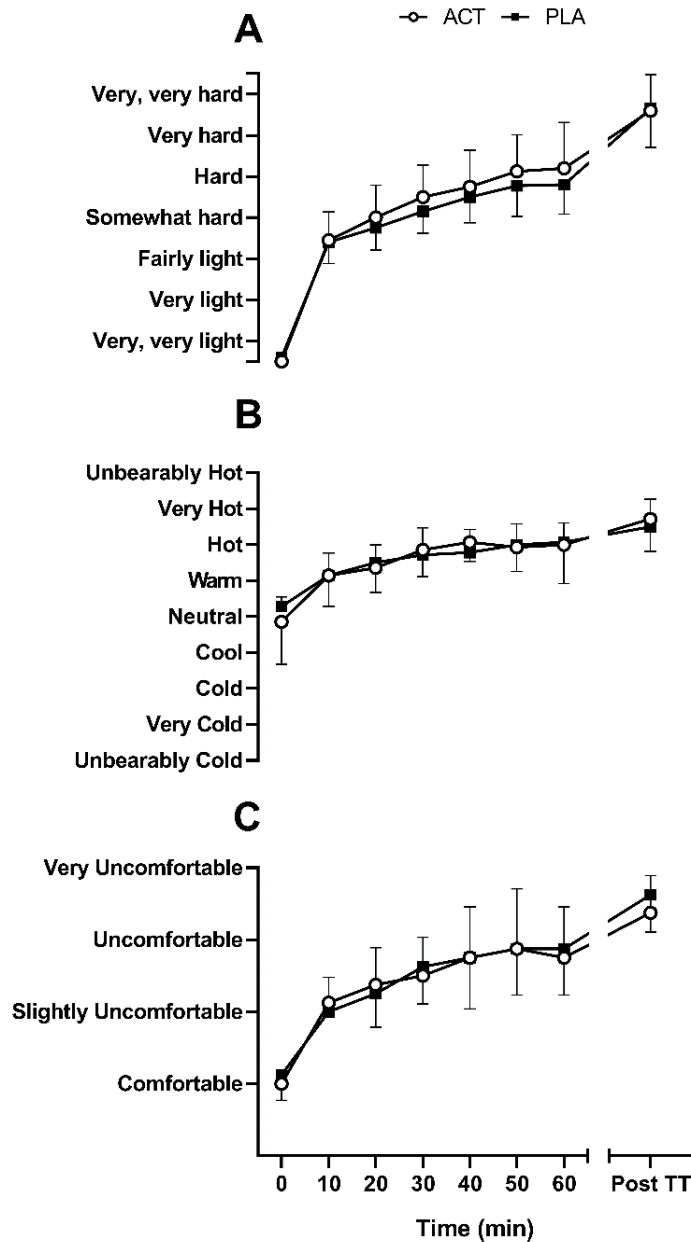
There was a main effect of time ( $p < 0.001$ ) for HR which increased and was highly comparable between conditions during steady state cycling (ACT:  $157 \pm 12$  bpm, PLA:  $157 \pm 13$  bpm) and the time trial (ACT:  $175 \pm 12$  bpm, PLA:  $177 \pm 12$  bpm). There was no difference in heart rate between conditions (interaction effect:  $p > 0.999$ , main effect:  $p = 0.860$ , Figure 3.4C).



**Figure 3.4** Core temperature (A), skin temperature (B) and heart rate (C) responses in hot and humid conditions of endurance trained triathletes (A:  $n = 11$ , B:  $n = 9$ , C:  $n = 10$ ) during ~60 min steady state cycling (63% peak power output) and a cycling time-trial ( $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$ ) after consuming  $20 \text{ mg} \cdot \text{kg} \text{ BM}^{-1}$  of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) and placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). Data are mean  $\pm$  standard deviation and were analysed using two-way repeated measures ANOVA (condition  $\times$  time) with post-hoc Bonferroni procedure for multiple comparisons ( $P < 0.05$ ).

### 3.4.3 Rating of Perceived Exertion, Thermal Sensation and Thermal Comfort

There was no difference in perceived exertion between conditions ( $p = 0.666$ ) despite small effects for increased RPE during steady state cycling in the acetaminophen trial at 20 min ( $\Delta 0.5 \pm 1.9$  AU,  $d = 0.26$ ), 30 min ( $\Delta 0.7 \pm 1.9$  AU,  $d = 0.37$ ), 40 min ( $\Delta 0.5 \pm 2.2$  AU,  $d = 0.23$ ), 50 min ( $\Delta 0.7 \pm 2.3$  AU,  $d = 0.3$ ) and 60 min ( $\Delta 0.8 \pm 2.6$  AU,  $d = 0.3$ ; Figure 3.5A). There was a main effect of time for RPE (main effect:  $p < 0.001$ ) increasing above pre-exercise levels throughout steady state cycling (ACT:  $15.3 \pm 2.1$  AU, PLA:  $14.5 \pm 1.4$  AU), and was higher after the time trial (ACT:  $17.8 \pm 2.1$  AU, PLA:  $18.3 \pm 1.9$  AU). Thermal sensation was also not different between conditions ( $p = 0.681$ ) but there was a similar small effect for reduced thermal sensation at commencement of the ACT condition compared with PLA ( $\Delta -0.4 \pm 1.2$  AU,  $d = -0.35$ ) and an increase after 40 min of steady state cycling ( $\Delta 0.3 \pm 0.8$  AU,  $d = 0.34$ ; Figure 3.5B). There was a main effect of time for thermal sensation and comfort (main effect:  $p < 0.001$ ) with similar maximum thermal comfort values that were not different between the ACT ( $3.5 \pm 0.5$  AU) and PLA conditions ( $3.7 \pm 0.5$  AU; Figure 3.5C).



**Figure 3.5** Rating of perceived exertion (A), thermal sensation (B) and thermal comfort (C) of endurance trained triathletes (A:  $n = 10$ , B and C:  $n = 7$ ) in hot and humid conditions during ~60 min steady state cycling (63% peak power output) and  $7 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{BM}^{-1}$  time trial after consuming a  $20 \text{ mg} \cdot \text{kg} \text{ BM}^{-1}$  dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\% \text{ RH}$ ) or placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\% \text{ RH}$ ). Data are mean  $\pm$  standard deviation and were analysed using two-way repeated measures ANOVA (condition  $\times$  time) with post-hoc Bonferroni analyses for multiple comparisons with alpha set  $P < 0.05$ .



### 3.4.4 Fluid Balance

Participants were euhydrated upon arrival for each experimental trial (USG: ACT 1.015; PLA 1.016) with USG similar between conditions ( $p = 0.636$ ). There was a reduction in body mass in both conditions (ACT:  $\Delta 1.25 \pm 0.6$  kg,  $d = 2.2$ ,  $p < 0.001$ ; PLA:  $\Delta 1.25 \pm 0.7$  kg,  $d = 1.8$ ,  $p < 0.001$ ), however fluid ingestion ( $p = 0.505$ ) and WBSR (ACT:  $1.9 \pm 0.5$  L·h<sup>-1</sup>, PLA:  $1.9 \pm 0.6$  L·h<sup>-1</sup>,  $p = 0.930$ ) were not different between acetaminophen and placebo conditions (Table 3.2).

**Table 3.2** Waking urine specific gravity, fluid consumption, fluid loss, body mass change and sweat rate of endurance trained triathletes ( $n = 11$ ) in hot and humid conditions during ~60 min cycling bout (63% peak power output) followed by a time trial (7 kJ·kg<sup>-1</sup>·BM<sup>-1</sup>) after consuming either a 20 mg·kg BM<sup>-1</sup> dose of acetaminophen (ACT,  $29.9 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.7\%$  RH) or placebo (PLA,  $29.7 \pm 0.7^\circ\text{C}$ ,  $68.7 \pm 2.8\%$  RH). Data are mean  $\pm$  standard deviation and were analysed using paired Student's t-tests with alpha set at 0.05.

	Acetaminophen	Placebo	Cohen's $d$	p-value
Urine Specific Gravity	1.015 (0.003)	1.016 (0.004)	0.29	0.636
Total Fluid Consumption (L)	1.69 (0.36)	1.73 (0.42)	0.10	0.505
Time Trial Fluid Consumption (L)	0.48 (0.28)	0.52 (0.34)	0.13	0.505
Total Fluid Loss (L)	2.94 (0.73)	2.86 (0.93)	0.10	0.623
Body Mass Change (%)	-1.82 (0.8)	-1.83 (1.0)	0.01	0.990
Sweat Rate (L/h)	1.9 (0.5)	1.9 (0.6)	0.00	0.930

### 3.5 Discussion

This study determined the effect of acetaminophen ingestion on physiological responses, thermal perception and cycling time-trial performance of endurance trained athletes in hot and humid conditions. The major findings of the present study were that acetaminophen ingestion had no meaningful impact on core or skin temperature, and psychometric ratings of RPE, thermal sensation and thermal comfort. Moreover, there was a moderate effect for poorer endurance performance in the heat with acetaminophen ingestion. Accordingly, this indicates that ingestion of acetaminophen in close temporal proximity to endurance performance may be contraindicated and does not appear to have any practical ergogenic utility to improve endurance cycling performance in hot and humid conditions for endurance trained athletes.

There is a paucity of data available on the effect of acetaminophen on exercise capacity and performance. Intuitively, the antipyretic and/or analgesic effects of acetaminophen might be expected to ameliorate the detrimental physiological and/or perceptual responses associated with exercise in the heat. For example, a purported mechanism of action with acetaminophen ingestion as an antipyretic compound is the inhibition of cyclooxygenase (COX) enzymes. The inhibition of COX enzymes may attenuate prostaglandin release, a response that induces fever and amplifies neural signals perceived as pain associated with the inflammatory response (Toussaint et al., 2010; Yagami, Koma, & Yamamoto, 2015). Moreover, Bradford et al. (2007) have shown that ingestion of a COX-2 inhibitor reduces core temperature and skin temperature during steady-state endurance exercise, creating a pharmacological “heat sink” to tolerate greater thermal stress. However, others have shown no difference in core temperature between acetaminophen and a placebo at rest in cold conditions (Foster et al., 2017) nor during 1 h moderate intensity, steady state exercise in hot and humid conditions (Coombs et al., 2015). The present study provides new data to support the contention that acetaminophen does not

have antipyretic effects in afebrile individuals exercising in hot conditions by showing no effect of acetaminophen ingestion on core or skin temperature.

The analgesic effect of acetaminophen acts to attenuate perceptions of pain (Mauger et al., 2010; Mauger et al., 2014) and corticospinal excitability (Mauger & Hopker, 2013), effects with potential to suppress perceptions of central fatigue and/or discomfort during high intensity exercise for improved performance. Mauger and colleagues (2014) employed a similar pre-exercise acetaminophen ingestion protocol as the present study and reported a ~17% improvement in time to exhaustion (~25 min) in recreationally active individuals in hot conditions (~30°C and ~50% RH; Mauger et al., 2014). However, an important distinction from the present study is the duration of heat exposure (~25 vs. ~120 min), with the self-paced cycling time trial in our study undertaken after an initial ~75 min period in the heat. Acetaminophen ingestion has also been associated with a ~2% improvement in a ~16 km time trial under temperate conditions (Mauger et al., 2010). While differences in experimental design and training status of participants may explain, at least in part, the lack of agreement between studies the divergent thermal stress, evidenced by higher mean core temperature and maximum skin temperature in the present study, is also a significant mitigating factor (Mauger et al., 2014). Moreover, the data shows no difference in perceptual measures including rating of perceived exertion, thermal sensation, and thermal comfort throughout the 1 h steady state cycling bout and after completion of the time-trial, variables that should reflect analgesia if acetaminophen was effective. The exclusion of perceived pain measurements is a limitation of the study design as these data would have provided greater clarity on the extent of the analgesic effects of acetaminophen during exercise in a hot environment. While few studies have determined the effects of acetaminophen on exercise performance, collectively the available data indicate that there is little evidence supporting acetaminophen as an effective ergogenic

aid in hot and humid conditions when trained athletes undertake prolonged, high intensity exercise similar to the demands of competition.

The moderate effect for poorer time trial performance in the heat in the acetaminophen trial of the present study is difficult to reconcile. A limitation of this study was no direct measurement of plasma acetaminophen concentration during the experimental trials, so the dose-dependent circulating acetaminophen is unknown. However, Foster et al. (2016) have shown ingestion of 20 mg·kg BM<sup>-1</sup> of acetaminophen after a small, standardised meal induced peak plasma acetaminophen concentration at rest between 100 and 120 min after ingestion and reduced core temperature by ~0.2°C. The protocol was designed to ensure plasma acetaminophen was high during exercise by consuming it 30 min after a standardised meal (1.5g/kg CHO, 600mL fluid) and commencing the time-trial 120 min after acetaminophen ingestion to coincide with peak plasma concentration. A possible explanation for reduced time trial performance in endurance trained athletes participating in the present study is that acetaminophen may have attenuated sensory feedback to reduce the capacity for self-pacing if such a “central governor” mechanism exists. If changes to perception did influence performance, the perceived exertion and thermal sensation/comfort scales lacked the sensitivity to identify a change in response between trials. Alternately, the duration of exposure to heat and humidity together with high intensity exercise resulted in high sweat rates and dehydration. Indeed, there was significant fluid loss during the experimental trials with sweat rates higher than reported in elite triathletes during an Olympic distance event in temperate conditions (Logan-Sprenger, 2019). Nonetheless, the fluid loss in the present study was highly comparable between trials and is unlikely to have contributed to the decrease in performance with acetaminophen compared with placebo. Clearly, further work is needed to elucidate the interactions between the environment, exercise task, hydration status and pharmacological responses to determine whether acetaminophen reduces performance capacity in endurance trained athletes.

In conclusion, the present study shows that  $20\text{mg}\cdot\text{kg}^{-1}$  acetaminophen ingested 60 min prior to exercise is not an effective ergogenic aid for trained endurance athletes completing an ~120 min endurance exercise bout mimicking Olympic distance triathlon in hot and humid conditions. Specifically, the antipyretic and analgesic effects typically associated with acetaminophen did not reduce core temperature, skin temperature, and perceptual measures of exertion or thermal stress, and there was also no apparent beneficial effect on steady state endurance cycling nor cycling time trial performance. Accordingly, these novel findings provide evidence that purported pharmaceutical ergogenic aids, specifically acetaminophen, for elite performance may not be effective in ecologically valid contexts and existing pre- and per-cooling strategies appear to be more appropriate for endurance exercise in the heat.

---

## **Chapter 4**

### Summary and Conclusion

---

The primary aim of this thesis was to evaluate the thermoregulatory strain and performance of elite athletes in environmental conditions experienced during training and competition. This was achieved through two studies which determined 1) the effect of divergent conditions on thermoregulation and training performance of highly trained swimmers undertaking high intensity training and 2) whether acetaminophen (paracetamol) ingestion increases the endurance cycling performance of trained triathletes in hot and humid conditions.

The first study (Chapter 2) characterised the effect of varied environmental conditions on thermoregulation and training performance in trained swimmers. Briefly, a group of elite swimmers and a group of sub-elite swimmers completed independent matched training sessions in different environmental conditions whilst gastrointestinal and skin temperature, perceived thermal sensation and comfort, fluid balance and training performance were recorded. Based on previous studies undertaken in aquatic environments, it was hypothesised that lower gastrointestinal and skin temperature, thermal sensation and comfort would occur in cold conditions compared to warm conditions. Consequently, performance was expected to be slower in cold conditions due to reductions in voluntary force production and neural drive.

Ambient temperature was the predominant environmental variable that differed between trials for both swimming groups and water temperature remained similar across all trials. The study found that skin temperature and thermal sensation were different between conditions. However, the lower skin temperature and thermal perception in cool/cold environments did not significantly compromise training performance. Therefore, the hypotheses that cold environmental conditions would decrease sprint swim training performance was not supported by the data.

This study is the first to show that elite swimming performance is maintained despite variation in ambient temperature, thermal perception and skin temperature between seasons. Whilst the

small to moderate differences (1.7-3.3%) were outside of typical variation for an elite swimmer, it seems likely this was impacted by changes in adaptive state and the technical error in manual timing. The data indicates that the performance of most swimmers who train outdoors in temperate and cooler climates and compete at a national and international level, such as southern hemisphere swimmers preparing during winter for major competition in northern hemisphere summer, will not be significantly compromised even when swimmers feel cold. Pre-heating the body using heating jackets, hot water immersion or changing to an indoor location may be an effective and worthwhile strategy if an increase in thermal perception is desired. Importantly, these results indicate that training intensity and subsequent adaptation can be maintained during periods of cool/cold conditions. Recording the response of cardiovascular and neuromuscular systems using heart rate, rate of force development or power output in each condition may have provided data to determine whether there were differences in physiological strain between environments with potential to affect the training response. Undertaking further studies to understand the interaction between environmental conditions, physiological strain and swimming training performance could elucidate whether adaptation to a training stimulus is consistent when training outdoors or if changes in thermal perception and skin temperature can influence training adaptation and competition performance.

Ambient temperature dependent differences in pre-training skin temperature and thermal sensation were maintained throughout the observed swim training sessions and could have influenced sprint swimming performance for some highly trained swimmers. Increases in gastrointestinal temperature before or during the main set were observed in each condition alongside the differences in skin temperature and thermal sensation. This suggests that the regulation of self-paced swimming performance during outdoor training could be dependent on afferent feedback from deep body temperature, skin temperature and thermal perception rather than deep body temperature alone. The cool/cold ambient temperature ( $<16^{\circ}\text{C}$ ) may



have resulted in a pre-training skin temperature and thermal sensation which could not equilibrate to normal values in  $\sim 28^{\circ}\text{C}$  water temperature thus compromising neural drive and sprint performance. However, skin temperature measurement during swimming and neuromuscular measurements pre/post swimming training are required in future studies to corroborate this hypothesis. A study design that employs a more systematic approach with a range of water and ambient temperature is also required in future to establish if there is a relationship between environmental conditions and outdoor swim performance in elite athletes. Nevertheless, increasing muscle temperature via an appropriate warm-up and minimising reductions in pre-training skin temperature and thermal perception year-round could increase the consistency of sprint performance and subsequent adaptation for elite swimmers.

The second experimental study (Chapter 3) investigated the effect of acetaminophen on thermoregulation in hot and humid conditions during steady state and time trial cycling similar to the total duration of an Olympic distance triathlon. It was hypothesised that time trial performance would improve and gastrointestinal temperature, skin temperature and thermal sensation and comfort would be reduced in the acetaminophen trial. On the contrary, there was no difference in gastrointestinal or skin temperature, perceived thermal comfort and thermal sensation during steady state and time trial cycling. Surprisingly, time to completion for the  $7\text{kJ}\cdot\text{kg}^{-1}\cdot\text{BM}^{-1}$  time trial increased for most participants after acetaminophen ingestion suggesting that acetaminophen may be contraindicated as an ergogenic aid during endurance exercise in hot and humid conditions.

The findings of the study indicate that acetaminophen has little efficacy as an ergogenic aid during endurance exercise undertaken by trained athletes in hot and humid conditions. Importantly, acetaminophen had no effect on gastrointestinal and skin temperature or thermal comfort and sensation of triathletes during endurance exercise. Therefore, this study does not

support the contention that acetaminophen ingestion reduces thermal strain during endurance exercise. Moreover, acetaminophen failed to regulate gastrointestinal or skin temperature despite its purported anti-pyretic effects. It seems the sustained heat production due to the high metabolic demands of prolonged high intensity work causes net heat storage in trained triathletes that is not attenuated by a pharmacological intervention. As such, the ergogenic effects of acetaminophen may be inconsequential for highly trained endurance athletes due to the magnitude of cooling required to reduce gastrointestinal and skin temperature in hot and humid environmental conditions during endurance competition.

Few studies have described the effects of acetaminophen on human physiology during exercise. Therefore, explaining the poorer endurance performance in this study compared with previous experimental trials is difficult. The absence of any differences in tissue temperature, thermal perception and fluid balance between experimental conditions in the current study appears to discount the possibility of attributing the performance effect to a change in thermal strain. A plausible explanation could be that reduced afferent feedback mechanisms relied upon by elite endurance athletes for effective pacing altered the pacing strategy of individuals during the acetaminophen trial. Regardless of the underlying mechanism, the finding that endurance exercise performance in the heat does not improve in trained individuals after ingestion of acetaminophen is novel.

This thesis determined the effect of thermal strain on elite athletes in both an applied and laboratory setting which presented common and independent limitations. The sample size was limited in large part due to the restricted availability of athletes and priority given to competition and training schedules which reduced the statistical power of each study. Constraints of the high-performance cohort also meant that swimming training sessions were observed during different phases of the periodised training plan to ensure divergent

environmental conditions for the applied swimming study. Therefore, differences in adaptation status and/or fitness may have affected training performance. Additionally, skin temperature could not be collected continuously during swimming due to the technological limitations of conducting research *in situ*, so skin temperature was restricted to thermal imaging ‘snapshots’. During the ~2 min transition between exiting the pool and taking an image the skin may have equilibrated to the ambient temperature which decreases the validity of the measure. Alternately, competition demands of Olympic-distance triathlon were replicated using an indoor cycling ergometer during the acetaminophen trial which has moderate external validity but experimental trials during outdoor competitions would have enhanced the relevance to racing conditions. Finally, plasma acetaminophen concentration was not measured during the cycling trials therefore it is unknown whether circulating acetaminophen was adequately absorbed and matched between trials.

Overall, the studies outlined in the present thesis provide new data on the thermoregulation of highly trained athletes during training and competition with the results exposing several areas for future research. Swimming performance during outdoor training was unchanged in cool/cold ambient temperatures. The efficacy of different methods to minimise the effect of cold conditions on thermal perception and whether this will have an ergogenic effect are less clear and may be important for swimmers who consistently train outdoors during winter months and are sensitive to cold conditions. For example, using substances known to elucidate a warm sensation on the skin such as capsaicin before high intensity swimming or swimming in an alternate swimsuit to minimise heat loss are methods which may enhance performance by increasing and/or maintaining skin temperature and thermal sensation during cool/cold conditions. Applied studies with adequate control, methodology and performance measures conducted during outdoor swim training sessions are required to determine the efficacy of any practical ergogenic aids. For example, replication of study one during swimming training

sessions with either 1) different swim training sessions in similar environmental conditions or 2) matched training sessions conducted in more varied environmental conditions (direct afternoon sun during summer, cold winter morning) would provide meaningful insight into the interaction between human thermoregulation and swimming performance in outdoor swim training. Additionally, the extent to which thermal sensation and skin temperature affect exercise performance in both terrestrial and aquatic environments require more scrutiny. Further investigation would increase the understanding of the determinants of the performance of self-paced exercise in challenging environmental conditions.

Acetaminophen did not increase performance or provide a per-cooling effect during an Olympic-distance triathlon completed by trained individuals. Future studies assessing its use in hot conditions during cycling trials of different durations such as those mimicking sprint or Ironman distance triathlons may provide a context where its application as a per-cooling agent is identified. Additionally, investigating the use of acetaminophen during other exercise modalities such as running or in competition would help determine its impact as an ergogenic aid during endurance exercise. For endurance athletes, future studies of pre- and per-cooling methods should continue to be focused on developing and testing the cooling and performance effect of innovative strategies which can be implemented practically given the constraints of the competition environment.

In conclusion, environmental conditions can present unique but significant thermoregulatory challenges for elite athletes during training and competition. Specifically, ambient temperature affects skin temperature and thermal sensation during outdoor swimming training and increased heat storage and gastrointestinal temperature in terrestrial environments require novel cooling strategies with large cooling effects to overcome thermal strain. External validity of exercise studies assessing thermal strain in an environment which does not match the

conditions of competition or training can be overstated. Therefore, whilst controlled laboratory studies can provide some insight into the underlying physiological limitations of exercise in challenging environmental conditions, well planned applied studies are required to translate these findings into a practical setting. Clearly, the studies in this thesis emphasise the importance of testing the effect of environmental conditions and ergogenic aids on the physiology and performance of elite athletes. They show that thermal strain can be specific to the exercise mode, environmental conditions and exercise intensity. Most importantly, the thermal response to the environment can alter performance during training and competition in elite athletes and strategies to overcome these effects will assist sport scientists and coaches during training and in preparation for competition to optimise athlete performance capacity.

---

## **Chapter 5**

### Bibliography

---

- Abbiss, C. R., Burnett, A., Nosaka, K., Green, J. P., Foster, J. K., & Laursen, P. B. (2010). Effect of hot versus cold climates on power output, muscle activation, and perceived fatigue during a dynamic 100-km cycling trial. *Journal of Sports Sciences*, 28(2), 117-125. doi:10.1080/02640410903406216
- Alhadad, S. B., Tan, P. M. S., & Lee, J. K. W. (2019). Efficacy of Heat Mitigation Strategies on Core Temperature and Endurance Exercise: A Meta-Analysis. *Frontiers in Physiology*, 10, 71.
- Alhammoud, M., Oksa, J., Morel, B., Hansen, C., Chastan, D., & Racinais, S. (2020). Thermoregulation and shivering responses in elite alpine skiers. *European Journal of Sport Science*, 1-12. doi:10.1080/17461391.2020.1754470
- Altareki, N., Drust, B., Atkinson, G., Cable, T., & Gregson, W. (2009). Effects of environmental heat stress (35 degrees C) with simulated air movement on the thermoregulatory responses during a 4-km cycling time trial. *International Journal of Sports Medicine*, 30(1), 9-15. doi:10.1055/s-2008-1038768
- Amano, T., Okushima, D., Breese, B. C., Bailey, S. J., Koga, S., & Kondo, N. (2018). Influence of dietary nitrate supplementation on local sweating and cutaneous vascular responses during exercise in a hot environment. *European Journal of Applied Physiology*, 118(8), 1579-1588. doi:10.1007/s00421-018-3889-9
- Anderson, B. J. (2008). Paracetamol (Acetaminophen): mechanisms of action. *Pediatric Anesthesia*, 18(10), 915-921. doi:10.1111/j.1460-9592.2008.02764.x
- Angel Rodriguez, M., Victor Piedra, J., Sanchez-Fernandez, M., del Valle, M., Crespo, I., & Olmedillas, H. (2020). A Matter of Degrees: A Systematic Review of the Ergogenic Effect of Pre-Cooling in Highly Trained Athletes. *International Journal of Environmental Research and Public Health*, 17(8), 2952. doi:10.3390/ijerph17082952

- Australian Bureau of Meteorology. (2020). Mean temperature change in Australia from 1970 to 2019. In M. t. c. i. A. f. t. 2019 (Ed.).  
<http://www.bom.gov.au/climate/change/?ref=fr#tabs=Tracker&tracker=trend-maps>:  
 Australian Bureau of Meteorology,.
- Bach, A. J. E., Stewart, I. B., Disher, A. E., & Costello, J. T. (2015). A Comparison between Conductive and Infrared Devices for Measuring Mean Skin Temperature at Rest, during Exercise in the Heat, and Recovery. *PLoS ONE*, *10*(2), e0117907.  
 doi:10.1371/journal.pone.0117907
- Bergeron, M. F., Bahr, R., Bärtsch, P., Bourdon, L., Calbet, J. A. L., Carlsen, K. H., . . . Engebretsen, L. (2012). International Olympic Committee consensus statement on thermoregulatory and altitude challenges for high-level athletes. *British Journal of Sports Medicine*, *46*(11), 770-779. doi:10.1136/bjsports-2012-091296
- Bernard, T. E. (1999). Prediction of Workplace Wet Bulb Global Temperature. *Applied Occupational and Environmental Hygiene*, *14*(2), 126–134.  
<https://doi.org/10.1080/104732299303296>
- Bijker, K. E., de Groot, G., & Hollander, A. P. (2001). Delta efficiencies of running and cycling. *Medicine and Science in Sports and Exercise*, *33*(9), 1546-1551.  
 doi:10.1097/00005768-200109000-00019
- Bongers CCWG, Daanen HAM, Bogerd CP, Hopman MTE, and Eijsvogels TMH. (2018). Validity, Reliability, and Inertia of Four Different Temperature Capsule Systems. *Medicine and Science in Sport and Exercise*, *50*(1), 169-175
- Bongers, C. C. W. G., Hopman, M. T. E., & Eijsvogels, T. M. H. (2017). Cooling interventions for athletes: An overview of effectiveness, physiological mechanisms, and practical considerations. *Temperature (Austin)*, *4*(1), 60-78.  
 doi:10.1080/23328940.2016.1277003



- Bongers, C. C. W. G., Thijssen, D. H. J., Veltmeijer, M. T. W., Hopman, M. T. E., & Eijssvogels, T. M. H. (2015). Precooling and percooling (cooling during exercise) both improve performance in the heat: a meta-analytical review. *British Journal of Sports Medicine*, 49(6), 377. doi:10.1136/bjsports-2013-092928
- Bradford, C. (2018). *Acute and adaptive responses to endurance swimming in warm water*. University of Otago,
- Bradford, C., Cotter, J. D., Thorburn, M. S., Walker, R. J., & Gerrard, D. F. (2007). Exercise can be pyrogenic in humans. *American Journal of Physiology - Regulatory Integrative Comparative Physiology*, 292(1), R143-149. doi:10.1152/ajpregu.00926.2005
- Brotherhood, J. R. (2008). Heat stress and strain in exercise and sport. *Journal of Science and Medicine in Sport*, 11(1), 6-19. doi:10.1016/j.jsams.2007.08.017
- Castle, P. C., Maxwell, N., Allchorn, A., Mauger, A. R., & White, D. K. (2012). Deception of ambient and body core temperature improves self paced cycling in hot, humid conditions. *European Journal of Applied Physiology*, 112(1), 377-385. doi:10.1007/s00421-011-1988-y
- Chalmers, S., & Jay, O. (2018). Australian community sport extreme heat policies: Limitations and opportunities for improvement. *Journal of Science and Medicine in Sport*, 21(6), 544-548. doi:10.1016/j.jsams.2018.01.003
- Chan, K. O. W., Wong, S. H. S., & Chen, Y. J. (2008). Effects of a hot environment on simulated cycling and running performance in triathletes. *Journal of Sports Medicine and Physical Fitness*, 48(2), 149-157.
- Che Muhamed, A. M., Atkins, K., Stannard, S. R., Mündel, T., & Thompson, M. W. (2016). The effects of a systematic increase in relative humidity on thermoregulatory and circulatory responses during prolonged running exercise in the heat. *Temperature (Austin)*, 3(3), 455-464. doi:10.1080/23328940.2016.1182669

- Che Muhamed, A. M., Yusof, H. A., Stannard, S. R., Mündel, T., & Thompson, M. W. (2019). The Efficacy of Ingesting Water on Thermoregulatory Responses and Running Performance in a Warm-Humid Condition. *Frontiers in Physiology*, 10, 507-507. doi:10.3389/fphys.2019.00507
- Cheung, S. (2010). *Advanced Environmental Exercise Physiology*. Champaign, IL: Human Kinetics.
- Cheung, S. (2010). Interconnections between thermal perception and exercise capacity in the heat. *Scandinavian Journal of Medicine & Science in Sports*, 20(s3), 53-59. doi:10.1111/j.1600-0838.2010.01209.x
- Cheuvront, S., Carter, R., Castellani, J. W., & Sawka, M. N. (2005). Hypohydration impairs endurance exercise performance in temperate but not cold air. *Journal of Applied Physiology*, 99(5), 1972-1976. doi:10.1152/jappphysiol.00329.2005
- Cheuvront, S. N., & Haymes, E. M. (2001). Thermoregulation and Marathon Running: Biological and Environmental Influences. *Sports Medicine*, 31(10), 743–762. doi:10.2165/00007256-200131100-00004
- Choo, H. C., Peiffer, J. J., Lopes-Silva, J. P., Mesquita, R. N. O., Amano, T., Kondo, N., & Abbiss, C. R. (2019). Effect of ice slushy ingestion and cold water immersion on thermoregulatory behavior. *PLoS ONE*, 14(2), e0212966-e0212966. doi:10.1371/journal.pone.0212966
- Chou, T.-H., Akins, J. D., Crawford, C. K., Allen, J. R., & Coyle, E. F. (2019). Low Stroke Volume during Exercise with Hot Skin Is Due to Elevated Heart Rate. *Medicine and Science in Sports and Exercise*, 51(10), 2025-2032. doi:10.1249/MSS.0000000000002029
- Cohen, J. (2013). *Statistical Power Analysis for the Behavioral Sciences*. Burlington: Elsevier Science.

- Coombs, G. B., Cramer, M. N., Ravanelli, N. M., Morris, N. B., & Jay, O. (2015). Acute acetaminophen ingestion does not alter core temperature or sweating during exercise in hot–humid conditions. *Scandinavian Journal of Medicine & Science in Sports*, 25, 96-103. doi:10.1111/sms.12336
- Costello, J. T., Culligan, K., Selfe, J., & Donnelly, A. E. (2012). Muscle, Skin and Core Temperature after –110°C Cold Air and 8°C Water Treatment. *PLoS ONE*, 7(11), e48190-e48190. doi:10.1371/journal.pone.0048190
- Costill, D. L., Cahill, P. J., & Eddy, D. (1967). Metabolic responses to submaximal exercise in three water temperatures. *Journal of Applied Physiology*, 22(4), 628-632. doi:10.1152/jappl.1967.22.4.628
- Cox, G.R., Desbrow, B., Montgomery, P.G., Anderson, M.E., Bruce, C.R., Macrides, T.A....Burke, L. (2002) Effect of different protocols of caffeine intake on metabolism and endurance performance. *Journal of Applied Physiology*, 93(1), 990-999
- Cramer, M. N., & Jay, O. (2016). Biophysical aspects of human thermoregulation during heat stress. *Autonomic Neuroscience: Basic and Clinical*, 196, 3-13. doi:10.1016/j.autneu.2016.03.001
- Crapo, R. O., Morris, A. H., Clayton, P. D., & Nixon, C. R. (1982). Lung volumes in healthy nonsmoking adults. *Bulletin Europeen de Physiopathologie Respiratoire*, 18(3), 419-425.
- Cuddy, J. S., Hailes, W. S., & Ruby, B. C. (2014). A reduced core to skin temperature gradient, not a critical core temperature, affects aerobic capacity in the heat. *Journal of Thermal Biology*, 43(1), 7-12. doi:10.1016/j.jtherbio.2014.04.002
- de Pauw, K., Roelands, B., Cheung, S. S., de Geus, B., Rietjens, G., & Meeusen, R. (2013). Guidelines to Classify Subject Groups in Sport-Science Research. *International*

*Journal of Sports Physiology and Performance*, 8(2), 111-122.

doi:10.1123/ijsp.8.2.111

Dixon, P. G., Kraemer, W. J., Volek, J. S., Howard, R. L., Gomez, A. L., Comstock, B. A., . .

. Maresh, C. M. (2010). The Impact of Cold-Water Immersion on Power Production in the Vertical Jump and the Benefits of a Dynamic Exercise Warm-Up. *Journal of Strength and Conditioning Research*, 24(12), 3313-3317.

doi:10.1519/JSC.0b013e3181f212e2

Drust, B., Rasmussen, P., Mohr, M., Nielsen, B., & Nybo, L. (2005). Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiologica Scandinavica*, 183(2), 181-190. doi:10.1111/j.1365-201X.2004.01390.x

*Scandinavica*, 183(2), 181-190. doi:10.1111/j.1365-201X.2004.01390.x

Eccles, R. (2000). Role of cold receptors and menthol in thirst, the drive to breathe and arousal. *Appetite*, 34(1), 29-35. doi:10.1006/appe.1999.0291

El Helou, N., Tafflet, M., Berthelot, G., Tolaini, J., Marc, A., Guillaume, M., . . . Toussaint, J.-F. (2012). Impact of Environmental Parameters on Marathon Running

Performance. *PLoS ONE*, 7(5), 1-9. doi:10.1371/journal.pone.0037407

Ely, B. R., & Cheuvront, S. N. (2010). Efficacy of Nutritional Ergogenic Aids in Hot Environments. *Current Topics in Nutraceutical Research*, 8(1), 1-6.

Ely, B. R., Cheuvront, S. N., Kenefick, R. W., & Sawka, M. N. (2010). Aerobic performance is degraded, despite modest hyperthermia, in hot environments. *Medicine and Science in Sports and Exercise*, 42(1), 135-141. doi:10.1249/MSS.0b013e3181adb9fb

Ely, B. R., Ely, M. R., Cheuvront, S. N., Kenefick, R. W., Degroot, D. W., & Montain, S. J.

(2009). Evidence against a 40 degrees C core temperature threshold for fatigue in humans. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, 107(5), 1519.

doi:10.1152/japplphysiol.00577.2009

- Ely, M. R., Cheuvront, S. N., & Montain, S. J. (2007). Neither cloud cover nor low solar loads are associated with fast marathon performance. *Medicine and Science in Sports and Exercise*, 39(11), 2029. doi:10.1249/mss.0b013e318149f2c3
- Ely, M. R., Cheuvront, S. N., Roberts, W. O., & Montain, S. J. (2007). Impact of weather on marathon-running performance. *Medicine and Science in Sports and Exercise*, 39(3), 487. doi:10.1249/mss.0b013e31802d3aba
- Esh, C. J., Christmas, B. C. R., Mauger, A. R., Cherif, A., Molphy, J., & Taylor, L. (2021). The influence of environmental and core temperature on cyclooxygenase and PGE2 in healthy humans. *Scientific Reports*, 11(1), 6531-6531. doi:10.1038/s41598-021-84563-5
- Esh, C. J., Mauger, A., Palfreeman, R. A., Al-Janubi, H., & Taylor, L. (2017). Acetaminophen (Paracetamol): Use beyond Pain Management and Dose Variability. *Frontiers in Physiology*, 8, 1092. doi:10.3389/fphys.2017.01092
- Faulkner, S. H., Broekhuijzen, I., Raccuglia, M., Hupperets, M., Hodder, S. G., & Havenith, G. (2019). The Threshold Ambient Temperature for the Use of Precooling to Improve Cycling Time-Trial Performance. *International Journal of Sports Physiology & Performance*, 14(3), 323-330.
- Filingeri, D. (2016). Neurophysiology of Skin Thermal Sensations. *Comprehensive Physiology*, 6(3), 1429. doi:10.1002/cphy.c150040
- Foster, J., Mauger, A., Govus, A., Hewson, D., & Taylor, L. (2017). Acetaminophen (Paracetamol) Induces Hypothermia During Acute Cold Stress. *Clinical Drug Investigation*, 37(11), 1055-1065. doi:10.1007/s40261-017-0560-x
- Foster, J., Mauger, A., Thomasson, K., White, S., & Taylor, L. (2016). Effect of acetaminophen ingestion on thermoregulation of normothermic, non-febrile humans. *Frontiers in Pharmacology*, 7(Generic), 54. doi:10.3389/fphar.2016.00054

- Fujishima, K., Shimizu, T., Ogaki, T., Hotta, N., Kanaya, S., Shono, T., & Ueda, T. (2001). Thermoregulatory Responses to Low-Intensity Prolonged Swimming in Water at Various Temperatures and Treadmill Walking on Land. *Journal of Physiological Anthropology and Applied Human Science*, 20(3), 199-206. doi:10.2114/jpa.20.199
- Gagge, A. P., Stolwijk, J. A. J., & Hardy, J. D. (1967). Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environmental Research*, 1(1), 1-20. doi:10.1016/0013-9351(67)90002-3
- Gagge, A. P., Stolwijk, J. A. J., & Saltin, B. (1969). Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures. *Environmental Research*, 2(3), 209-229. doi:https://doi.org/10.1016/0013-9351(69)90037-1
- Galbo, H., Houston, M. E., Christensen, N. J., Holst, J. J., Nielsen, B., Nygaard, E., & Suzuki, J. (1979). The effect of water temperature on the hormonal response to prolonged swimming. *Acta Physiologica Scandinavica*, 105(3), 326-337. doi:10.1111/j.1748-1716.1979.tb06348.x
- Galloway, S. D., & Maughan, R. J. (1997). Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Medicine and Science in Sports and Exercise*, 29(9), 1240. doi:10.1097/00005768-199709000-00018
- Ganio, M. S., Brown, C. M., Casa, D. J., Becker, S. M., Yeargin, S. W., McDermott, B. P., . . . Armstrong, L. E. M., Carl M. (2009). Validity and Reliability of Devices That Assess Body Temperature During Indoor Exercise in the Heat. *Journal of Athletic Training*, 44(2), 124-135.
- Garth, A. K., & Burke, L. M. (2013). What Do Athletes Drink During Competitive Sporting Activities? *Sports Medicine (Auckland)*, 43(7), 539-564. doi:10.1007/s40279-013-0028-y

- Girard, O., Bishop, D. J., & Racinais, S. (2013). Hot conditions improve power output during repeated cycling sprints without modifying neuromuscular fatigue characteristics. *European Journal of Applied Physiology*, 113(2), 359-369. doi:10.1007/s00421-012-2444-3
- Girard, O., Brocherie, F., & Bishop, D. J. (2015). Sprint performance under heat stress: A review. *Scandinavian Journal of Medicine & Science in Sports*, 25(S1), 79-89. doi:10.1111/sms.12437
- González-Alonso, J., & Calbet, J. A. (2003). Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation*, 107(6), 824-830.
- González-Alonso, J., & Calbet, J. A. L. (2003). Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation*, 107(6), 824. doi:10.1161/01.CIR.0000049746.29175.3F
- González-Alonso, J., Crandall, C. G., & Johnson, J. M. (2008). The cardiovascular challenge of exercising in the heat. *Journal of Physiology*, 586(1), 45-53. doi:10.1113/jphysiol.2007.142158
- González-Alonso, J., Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T., & Nielsen, B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, 86(3), 1032. doi:10.1152/jappl.1999.86.3.1032
- Grösch, S., Niederberger, E., & Geisslinger, G. (2017). Investigational drugs targeting the prostaglandin E2 signaling pathway for the treatment of inflammatory pain. *Expert Opinion on Investigational Drugs*, 26(1), 51-61. doi:10.1080/13543784.2017.1260544

- Guy, J., Deakin, G., Edwards, A., Miller, C., & Pyne, D. (2015). Adaptation to Hot Environmental Conditions: An Exploration of the Performance Basis, Procedures and Future Directions to Optimise Opportunities for Elite Athletes. *Sports Medicine*, 45(3), 303-311. doi:10.1007/s40279-014-0277-4
- Hanson, N. J., Carrière, D. M., Morgan, H. E., Smith, A. R., Michael, T. J., & Miller, M. G. (2018). Deception of Ambient Temperature Does Not Elicit Performance Benefits During a 5 km Run in Hot, Humid Conditions. *The Journal of Strength & Conditioning Research*, 32(8).
- Hawley, J. A., & Noakes, T. D. (1992). Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *European Journal of Applied Physiology*, 65(1), 79-83. doi:10.1007/BF01466278
- Henderson, M. J., Christmas, B. C. R., Stevens, C. J., Coutts, A. J., & Taylor, L. (2020). Changes in Core Temperature During an Elite Female Rugby Sevens Tournament. *International Journal of Sports Physiology and Performance*, 15(4), 1-580. doi:10.1123/ijsp.2019-0375
- Holmér, I., & Bergh, U. (1974). Metabolic and thermal response to swimming in water at varying temperatures. *Journal of Applied Physiology*, 37(5), 702. doi:10.1152/jappl.1974.37.5.702
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1), 3–12. <https://doi.org/10.1249/MSS.0b013e31818cb278>
- Hue, O., Antoine-Jonville, S., & Sara, F. (2007). The Effect of 8 Days of Training in Tropical Environment on Performance in Neutral Climate in Swimmers. *International Journal of Sports Medicine*, 28(1), 48-52. doi:10.1055/s-2006-923958



- Hue, O., Monjo, R., Lazzaro, M., Baillot, M., Hellard, P., Marlin, L., & Jean-Etienne, A. (2013). The effect of time of day on cold water ingestion by high-level swimmers in a tropical climate. *International Journal of Sports Physiology and Performance*, 8(4), 442. doi:10.1123/ijsp.8.4.442
- Hue, O., Monjo, R., & Riera, F. (2015). Imposed Cold-water Ingestion during Open Water Swimming in Internationally Ranked Swimmers. *International Journal of Sports Medicine*, 36(11), 941-946. doi:10.1055/s-0035-1548812
- Jeffries, O., & Waldron, M. (2019). The effects of menthol on exercise performance and thermal sensation: A meta-analysis. *Journal of Science and Medicine in Sport*, 22(6), 707-715. doi:10.1016/j.jsams.2018.12.002
- Jimenez-Perez, I., Gil-Calvo, M., Vardasca, R., Fernandes, R. J., & Vilas-Boas, J. P. (2021). Pre-exercise skin temperature evolution is not related with 100 m front crawl performance. *Journal of Thermal Biology*, 98, 102926–102926. <https://doi.org/10.1016/j.jtherbio.2021.102926>
- Jobson, S. A., Nevill, A. M., Palmer, G. S., Jeukendrup, A. E., Doherty, M., & Atkinson, G. (2007). The ecological validity of laboratory cycling: Does body size explain the difference between laboratory- and field-based cycling performance? *Journal of Sports Sciences*, 25(1), 3-9. doi:10.1080/02640410500520526
- Junge, N., Jørgensen, R., Flouris, A. D., & Nybo, L. (2016). Prolonged self-paced exercise in the heat – environmental factors affecting performance. *Temperature*, 3(4), 539-548. doi:10.1080/23328940.2016.1216257
- Kakamu, T., Wada, K., Smith, D. R., Endo, S., & Fukushima, T. (2017). Preventing heat illness in the anticipated hot climate of the Tokyo 2020 Summer Olympic Games. *Environmental Health and Preventive Medicine*, 22(1), doi:10.1186/s12199-017-0675-y

- Kerr, C. G., Trappe, T. A., Starling, R. D., & Trappe, S. W. (1998). Hyperthermia during olympic triathlon: Influence of body heat storage during the swimming stage. *Medicine and Science in Sports and Exercise*, 30(1), 99-104. doi:10.1097/00005768-199801000-00014
- Keyword, M., Emmerson, K., & Hibberd, M. (2016). Climate: Temperature. In: Australia state of the environment 2016. Retrieved from <https://soe.environment.gov.au/theme/climate/topic/2016/temperature>
- Laitano, O., Leon, L. R., Roberts, W. O., & Sawka, M. N. (2019). Controversies in exertional heat stroke diagnosis, prevention, and treatment. *Journal of Applied Physiology* (1985), 127(5), 1338-1348. doi:10.1152/jappphysiol.00452.2019
- Lee, J. K. W., Koh, A. C. H., Koh, S. X. T., Liu, G. J. X., Nio, A. Q. X., & Fan, P. W. P. (2014). Neck cooling and cognitive performance following exercise-induced hyperthermia. *European Journal of Applied Physiology*, 114(2), 375-384. doi:10.1007/s00421-013-2774-9
- Liljegren, J. C., Carhart, R. A., Lawday, P., Tschopp, S., & Sharp, R. (2008). Modeling the wet bulb globe temperature using standard meteorological measurements. *Journal of Occupational and Environmental Hygiene*, 5(10), 645-655. doi:10.1080/15459620802310770
- Lloyd, A., Hodder, S., & Havenith, G. (2015). The interactive effect of cooling and hypoxia on forearm fatigue development. *European Journal of Applied Physiology*, 115(9), 2007-2018. doi:10.1007/s00421-015-3181-1
- Logan-Sprenger, H. M. (2019). Fluid balance and thermoregulatory responses of competitive triathletes. *Journal of Thermal Biology*, 79, 69-72. doi:10.1016/j.jtherbio.2018.12.003

- Loniewski, I., Sawrymowicz, M., Pawlik, A., Wójcicki, J., & Drozdziak, M. (2001). Lack of effect of physical exercise on pharmacokinetics of acetaminophen tablets in healthy subjects. *Acta Poloniae Pharmaceutica*, 58(2), 141–144.
- Macaluso, F., di Felice, V., Boscaino, G., Bonsignore, G., Stampone, T., Farina, F., & Morici, G. (2011). Effects of three different water temperatures on dehydration in competitive swimmers. *Science and Sports*, 26(5), 265-271.  
doi:10.1016/j.scispo.2010.10.004
- Maia-Lima, A., Ramos, G. P., Moraes, M. M., Pacheco, D. A. S., de Oliveira, G. G. A., de Barros, C. L. M., . . . Garcia, E. S. (2017). Effects of Precooling on 30-km Cycling Performance and Pacing in Hot and Temperate Environments. *International Journal of Sports Medicine*, 38(1), 48-54. doi:10.1055/s-0042-113465
- Mauger, A., & Hopker, J. G. (2013). The effect of acetaminophen ingestion on cortico-spinal excitability. *Canadian Journal of Physiology and Pharmacology*, 91(2), 187-189.  
doi:10.1139/cjpp-2012-0213
- Mauger, A., Jones, A., & Williams, C. A. (2010). Influence of acetaminophen on performance during time trial cycling. *Journal of Applied Physiology*, 108(1), 98-104.  
doi:10.1152/jappphysiol.00761.2009
- Mauger, A., Taylor, L., Harding, C., Wright, B., Foster, J., & Castle, P. C. (2014). Acute acetaminophen (paracetamol) ingestion improves time to exhaustion during exercise in the heat. *Experimental Physiology*, 99(1), 164-171.  
doi:10.1113/expphysiol.2013.075275
- Maughan, R., Otani, H., & Watson, P. (2012). Influence of relative humidity on prolonged exercise capacity in a warm environment. *European Journal of Applied Physiology*, 112(6), 2313-2321. doi:10.1007/s00421-011-2206-7

- McArdle, W. D., Magel, J. R., Lesmes, G. R., & Pechar, G. S. (1976). Metabolic and cardiovascular adjustment to work in air and water at 18, 25, and 33 degrees C. *Journal of Applied Physiology*, 40(1), 85-90. doi:10.1152/jappl.1976.40.1.85
- McCann, D. J., & Adams, W. C. (1997). Wet bulb globe temperature index and performance in competitive distance runners. *Medicine and Science in Sports and Exercise*, 29(7), 955-961. doi:10.1097/00005768-199707000-00016
- McGowan, C.J., Pyne, D.B., Thompson, K.G., Raglin, J.S., Osborne, M., Rattray, B. (2017) Elite sprint swimming performance is enhanced by completion of additional warm-up activities. *Journal of Sports Sciences*, 35(1), 1493-1499.
- McGowan, C. J., Thompson, K. G., Pyne, D. B., Raglin, J. S., & Rattray, B. (2015). Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance. *Journal of Science and Medicine in Sport*, 19(4), 354–358. <https://doi.org/10.1016/j.jsams.2015.04.012>
- Meade, R. D., & Kenny, G. P. (2017). Are All Heat Loads Created Equal? *Medicine and Science in Sports and Exercise*, 49(9), 1796-1804. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=124667227&site=ehost-live&scope=site>
- Minett, G. M., Duffield, R., Marino, F. E., & Portus, M. (2011). Volume-dependent response of precooling for intermittent-sprint exercise in the heat. *Medicine and Science in Sports and Exercise*, 43(9), 1760-1769. doi:10.1249/MSS.0b013e318211be3e
- Mitchell, D., & Wyndham, C. H. (1969). Comparison of weighting formulas for calculating mean skin temperature. *Journal of Applied Physiology (1948)*, 26(5), 616-622. doi:10.1152/jappl.1969.26.5.616
- Moreira, D. G., Costello, J. T., Brito, C. J., Adamczyk, J. G., Ammer, K., Bach, A. J. E., . . . Sillero-Quintana, M. (2017). Thermographic imaging in sports and exercise medicine:

- A Delphi study and consensus statement on the measurement of human skin temperature. *Journal of Thermal Biology*, 69, 155-162.  
doi:10.1016/j.jtherbio.2017.07.006
- Nadel, E. R. (1984). Energy exchanges in water. *Undersea Biomedical Research*, 11(2), 149-158. Retrieved from <http://europepmc.org/abstract/MED/6485144>
- Nadel, E. R., Holmer, I., Bergh, U., Astrand, P. O., & Stolwijk, J. A. (1974). Energy exchanges of swimming man. *Journal of Applied Physiology*, 36(4), 465-471.  
doi:10.1152/jappl.1974.36.4.465
- Nana, A., Slater, G. J., Stewart, A. D., & Burke, L. M. (2015). Methodology review: using dual-energy X-ray absorptiometry (DXA) for the assessment of body composition in athletes and active people. *International Journal of Sport Nutrition and Exercise Metabolism*, 25(2), 198. doi:10.1123/ijsnem.2013-0228
- Nassis, G. P., & Geladas, N. D. (2002). Effect of water ingestion on cardiovascular and thermal responses to prolonged cycling and running in humans: a comparison. *European Journal of Applied Physiology*, 88(3), 227-234. doi:10.1007/s00421-002-0682-5
- Nimmo, M. (2004). Exercise in the cold. *Journal of Sports Sciences*, 22(10), 898-916.  
doi:10.1080/0264041400005883
- Nybo, L., Jensen, T., Nielsen, B., & González-Alonso, J. (2001). Effects of marked hyperthermia with and without dehydration on VO(2) kinetics during intense exercise. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, 90(3), 1057.  
doi:10.1152/jappl.2001.90.3.1057
- Nybo, L., & Nielsen, B. (2001). Hyperthermia and central fatigue during prolonged exercise in humans. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, 91(3), 1055.  
doi:10.1152/jappl.2001.91.3.1055

- Nybo, L., Secher, N. H., & Nielsen, B. (2002). Inadequate heat release from the human brain during prolonged exercise with hyperthermia. *Journal of Physiology*, 545(2), 697-704. doi:10.1113/jphysiol.2002.030023
- Otani, H., Kaya, M., Tamaki, A., Watson, P., & Maughan, R. (2016). Effects of solar radiation on endurance exercise capacity in a hot environment. *European Journal of Applied Physiology*, 116(4), 769-779. doi:10.1007/s00421-016-3335-9
- Parkin, J. M., Carey, M. F., Zhao, S., & Febbraio, M. A. (1999). Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise. *Journal of Applied Physiology*, 86(3), 902-908. doi:10.1152/jappl.1999.86.3.902
- Parouty, J., Al Haddad, H., Quod, M., Lepretre, P. M., Ahmaidi, S., & Buchheit, M. (2010). Effect of cold water immersion on 100-m sprint performance in well-trained swimmers. *European Journal of Applied Physiology*, 109(3), 483-490. doi:10.1007/s00421-010-1381-2
- Parsons, K. (2014). *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance, Third Edition*. <https://doi.org/10.1201/b16750>
- Peiffer, J. J., & Abbiss, C. R. (2011). Influence of environmental temperature on 40 km cycling time-trial performance. *International Journal of Sports Physiology and Performance*, 6(2), 208-220. doi:10.1123/ijsp.6.2.208
- Périard, J. D., Cramer, M. N., Chapman, P. G., Caillaud, C., & Thompson, M. W. (2011a). Cardiovascular strain impairs prolonged self-paced exercise in the heat. *Experimental Physiology*, 96(2), 134-144. doi:10.1113/expphysiol.2010.054213
- Périard, J. D., Cramer, M. N., Chapman, P. G., Caillaud, C., & Thompson, M. W. (2011b). Neuromuscular function following prolonged intense self-paced exercise in hot

- climatic conditions. *European Journal of Applied Physiology*, 111(8), 1561-1569.  
doi:10.1007/s00421-010-1781-3
- Périard, J. D., & Racinais, S. (2016). Performance and Pacing during Cycle Exercise in Hyperthermic and Hypoxic Conditions. *Medicine and Science in Sports and Exercise*, 48(5), 845-853. doi:10.1249/MSS.0000000000000839
- Périard, J. D., Stephenson, B. T., Goosey-Tolfrey, V. L., Nikopoulos, T., & Migliorini, S. (2020). *Beat the Heat*. Retrieved from  
[https://www.triathlon.org/uploads/docs/HTB\\_v11.pdf](https://www.triathlon.org/uploads/docs/HTB_v11.pdf)
- Pyne, D. B., Trewin, C. B., & Hopkins, W. G. (2004). Progression and variability of competitive performance of Olympic swimmers. *Journal of Sports Sciences*, 22(7), 613-620. doi:10.1080/02640410310001655822
- Racinais, S., Alonso, J.-M., Coutts, A., Flouris, A., Girard, O., González-Alonso, J., . . . Périard, J. (2015). Consensus Recommendations on Training and Competing in the Heat. *Sports Medicine*, 45(7), 925-938. doi:10.1007/s40279-015-0343-6
- Racinais, S., Ihsan, M., Taylor, L., Cardinale, M., Adami, P. E., Alonso, J. M., . . . Bermon, S. (2021). Hydration and cooling in elite athletes: relationship with performance, body mass loss and body temperatures during the Doha 2019 IAAF World Athletics Championships. *British Journal of Sports Medicine*, bjsports-2020-103613.  
doi:10.1136/bjsports-2020-103613
- Racinais, S., Moussay, S., Nichols, D., Travers, G., Belfekih, T., Schumacher, Y. O., & Périard, J. D. (2019). Core temperature up to 41.5°C during the UCI Road Cycling World Championships in the heat. *British Journal of Sports Medicine*, 53(7), 426.  
doi:10.1136/bjsports-2018-099881
- Racinais, S., Nichols, D., Travers, G., Moussay, S., Belfekih, T., Farooq, A., . . . Périard, J. D. (2020). Health status, heat preparation strategies and medical events among elite

- cyclists who competed in the heat at the 2016 UCI Road World Cycling Championships in Qatar. *British Journal of Sports Medicine*, 54(16), bjsports-2019-100781-101007. doi:10.1136/bjsports-2019-100781
- Racinais, S., & Oksa, J. (2010). Temperature and neuromuscular function. *Scandinavian Journal of Medicine & Science in Sports*, 20(3), 1-18. doi:10.1111/j.1600-0838.2010.01204.x
- Racinais, S., Périard, J. D., Karlsen, A., & Nybo, L. (2015). Effect of Heat and Heat Acclimatization on Cycling Time Trial Performance and Pacing. *Medicine and Science in Sports and Exercise*, 47(3), 601-606. doi:10.1249/MSS.0000000000000428
- Roberts, M. F., Wenger, C. B., Stolwijk, J. A., & Nadel, E. R. (1977). Skin blood flow and sweating changes following exercise training and heat acclimation. *Journal of Applied Physiology*, 43(1), 133-137. doi:10.1152/jappl.1977.43.1.133
- Robinson, S., & Somers, A. (1971). Temperature regulation in swimming. *Journal de Physiologie*, 63(3), 406.
- Ross, M., Abbiss, C., Laursen, P., Martin, D., & Burke, L. (2013). Precooling Methods and Their Effects on Athletic Performance: A Systematic Review and Practical Applications. *Sports Medicine (Auckland)*, 43(3), 207-225. doi:10.1007/s40279-012-0014-9
- Ross, M., Garvican, L. A., Jeacocke, N. A., Laursen, P. B., Abbiss, C. R., Martin, D. T., & Burke, L. M. (2011). Novel precooling strategy enhances time trial cycling in the heat. *Medicine and Science in Sports and Exercise*, 43(1), 123. doi:10.1249/MSS.0b013e3181e93210
- Ruddock, A., Robbins, B., Tew, G., Bourke, L., & Purvis, A. (2017). Practical Cooling Strategies During Continuous Exercise in Hot Environments: A Systematic Review



- and Meta-Analysis. *Sports Medicine (Auckland)*, 47(3), 517-532. doi:10.1007/s40279-016-0592-z
- Sargeant, A. J. (1987). Effect of muscle temperature on leg extension force and short-term power output in humans. *European Journal of Applied Physiology and Occupational Physiology*, 56(6), 693–698. <https://doi.org/10.1007/BF00424812>
- Saunders, A. G., Dugas, J. P., Tucker, R., Lambert, M. I., & Noakes, T. D. (2005). The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment. *Acta Physiologica Scandinavica*, 183(3), 241-255. doi:10.1111/j.1365-201X.2004.01400.x
- Sawka, M. N., Cheuvront, S. N., & Kenefick, R. W. (2012). High skin temperature and hypohydration impair aerobic performance. *Experimental Physiology*, 97(3), 327-332. doi:10.1113/expphysiol.2011.061002
- Sawka, M. N., Leon, L. R., Montain, S. J., & Sanna, L. A. (2011). Integrated Physiological Mechanisms of Exercise Performance, Adaptation, and Maladaptation to Heat Stress. In M. A. T. Army Research Institute Of Environmental Medicine Natick & D. Mountain Medicine (Eds.).
- Saycell, J., Lomax, M., Massey, H., & Tipton, M. (2018). Scientific rationale for changing lower water temperature limits for triathlon racing to 12°C with wetsuits and 16°C without wetsuits. *British Journal of Sports Medicine*, 52(11), 702–708. <https://doi.org/10.1136/bjsports-2017-098914>
- Saycell, J., Lomax, M., Massey, H., & Tipton, M. (2019). How cold is too cold? Establishing the minimum water temperature limits for marathon swim racing. *British Journal of Sports Medicine*, 53(17):1078-1084. doi:10.1136/bjsports-2018-099978
- Schlader, Z. J., Simmons, S. E., Stannard, S. R., & Mündel, T. (2011a). The independent roles of temperature and thermal perception in the control of human thermoregulatory

- behavior. *Physiology & Behavior*, 103(2), 217-224.  
doi:<https://doi.org/10.1016/j.physbeh.2011.02.002>
- Schlader, Z. J., Simmons, S. E., Stannard, S. R., & Mündel, T. (2011b). Skin temperature as a thermal controller of exercise intensity. *European Journal of Applied Physiology*, 111(8), 1631-1639. doi:10.1007/s00421-010-1791-1
- Schlader, Z. J., Stannard, S. R., & Mündel, T. (2010). Human thermoregulatory behavior during rest and exercise — A prospective review. *Physiology & Behavior*, 99(3), 269-275. doi:10.1016/j.physbeh.2009.12.003
- Schmit, C., Duffield, R., Hausswirth, C., Coutts, A. J., & Le Meur, Y. (2016). Pacing adjustments associated with familiarization: Heat versus temperate environments. *International Journal of Sports Physiology and Performance*, 11(7), 855-860. doi:10.1123/ijsp.2015-0572
- Siri, W. E. (1956). The Gross Composition of the Body. *Advances in Biological and Medical Physics*, 4, 239-280
- Skein, M., Duffield, R., Cannon, J., & Marino, F. E. (2011). Self-paced intermittent-sprint performance and pacing strategies following respective pre-cooling and heating. *European Journal of Applied Physiology*, 112(1), 253-266. doi:10.1007/s00421-011-1972-6
- Soligard, T., Schwellnus, S., Alonso, J.M., Bahr, R., Clarsen, B., Dijkstra, H.P.,...Engebretsen, L. (2016) How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *British Journal of Sports Medicine*, 50(1), 1030-1041. doi:10.1136/bjsports-2016-096581

- Somani, S. M., Gupta, S. K., Frank, S., & Corder, C. N. (1990). Effect of exercise on disposition and pharmacokinetics of drugs. *Drug Development Research*, 20(3), 251–275. <https://doi.org/10.1002/ddr.430200302>
- Stevens, C. J., Kittel, A., Sculley, D. V., Callister, R., Taylor, L., & Dascombe, B. J. (2017). Running performance in the heat is improved by similar magnitude with pre-exercise cold-water immersion and mid-exercise facial water spray. *Journal of Sports Sciences*, 35(8), 798-805. doi:10.1080/02640414.2016.1192294
- Stevens, C. J., Mauger, A. R., Hassmèn, P., & Taylor, L. (2018). Endurance Performance is Influenced by Perceptions of Pain and Temperature: Theory, Applications and Safety Considerations. *Sports Medicine (Auckland)*, 48(3), 525-537. doi:10.1007/s40279-017-0852-6
- Stevens, C. J., Taylor, L., & Dascombe, B. J. (2017). Cooling During Exercise: An Overlooked Strategy for Enhancing Endurance Performance in the Heat. *Sports Medicine (Auckland)*, 47(5), 829-841. doi:10.1007/s40279-016-0625-7
- Stevens, C. J., Thoseby, B., Sculley, D. V., Callister, R., Taylor, L., & Dascombe, B. J. (2016). Running performance and thermal sensation in the heat are improved with menthol mouth rinse but not ice slurry ingestion. *Scandinavian Journal of Medicine & Science in Sports*, 26(10), 1209-1216. doi:10.1111/sms.12555
- Tatterson, A. J., Hahn, A. G., Martini, D. T., & Febbraio, M. A. (2000). Effects of heat stress on physiological responses and exercise performance in elite cyclists. *Journal of Science and Medicine in Sport*, 3(2), 186-193. doi:10.1016/S1440-2440(00)80080-8
- Todd, G., Butler, J. E., Taylor, J. L., & Gandevia, S. C. (2005). Hyperthermia: a failure of the motor cortex and the muscle. *Journal of Physiology*, 563(2), 621-631. doi:10.1113/jphysiol.2004.077115

- Todd, G., Gordon, C. J., Groeller, H., & Taylor, N. A. S. (2014). Does intramuscular thermal feedback modulate eccrine sweating in exercising humans? *Acta Physiologica*, 212(1), 86-96.
- Toussaint, K., Yang, X. C., Zielinski, M. A., Reigle, K. L., Sacavage, S. D., Nagar, S., & Raffa, R. B. (2010). What do we (not) know about how paracetamol (acetaminophen) works? *Journal of Clinical Pharmacy and Therapeutics*, 35(6), 617-638.  
doi:10.1111/j.1365-2710.2009.01143.x
- Trangmar, S., & González-Alonso, J. (2019). Heat, Hydration and the Human Brain, Heart and Skeletal Muscles. *Sports Medicine*, 49(S1), 69-85. doi:10.1007/s40279-018-1033-y
- Trinity, J. D., Pahnke, M. D., Lee, J. F., & Coyle, E. F. (2010). Interaction of hyperthermia and heart rate on stroke volume during prolonged exercise. *Journal of Applied Physiology*, 109(3), 745-751. doi:10.1152/jappphysiol.00377.2010
- Tucker, R., Marle, T., Lambert, E. V., & Noakes, T. D. (2006). The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. *Journal of Physiology*, 574(3), 905-915.  
doi:10.1113/jphysiol.2005.101733
- Tucker, R., Rauch, L., Harley, Y. X. R., & Noakes, T. D. (2004). Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. *Pflügers Archiv*, 448(4), 422-430. doi:10.1007/s00424-004-1267-4
- Tyler, C. J., Sunderland, C., & Cheung, S. S. (2015). The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis. *British Journal of Sports Medicine*, 49(1), 7-13. doi:10.1136/bjsports-2012-091739

- Tyler, C. J., Wild, P., & Sunderland, C. (2010). Practical neck cooling and time-trial running performance in a hot environment. *European Journal of Applied Physiology*, 110(5), 1063-1074. doi:10.1007/s00421-010-1567-7
- VanHaitsma, T. A., Light, A. R., Light, K. C., Huguen, R. W., Yenchik, S., & White, A. T. (2016). Fatigue sensation and gene expression in trained cyclists following a 40 km time trial in the heat. *European Journal of Applied Physiology*, 116(3), 541-552. doi:10.1007/s00421-015-3311-9
- Veltmeijer, M. T. W., Veeneman, D., Bongers, C. C. C. W., Netea, M. G., van Der Meer, J. W., Eijsvogels, T. M. H., & Hopman, M. T. E. (2017). The Impact of Central and Peripheral Cyclooxygenase Enzyme Inhibition on Exercise-Induced Elevations in Core Body Temperature. *International Journal of Sports Physiology and Performance*, 12(5), 662. doi:10.1123/ijsp.2016-0382
- Wakabayashi, H., Osawa, M., Koga, S., Li, K., Sakaue, H., Sengoku, Y., & Takagi, H. (2018). Effects of muscle cooling on kinetics of pulmonary oxygen uptake and muscle deoxygenation at the onset of exercise. *Physiological Reports*, 6(21), n/a. doi:10.14814/phy2.13910
- Whipp, B., & Wasserman, K. (1972). Oxygen uptake kinetics for various intensities of constant-load work. *Journal of Applied Physiology (1948)*, 33(3), 351–356. doi:10.1152/jappl.1972.33.3.351
- World Anti-Doping Agency. (2021). *World Anti-Doping Code International Standard Prohibited List 2021*. www.wada-ama.org: World Anti-Doping Agency,
- Yagami, T., Koma, H., & Yamamoto, Y. (2015). Pathophysiological Roles of Cyclooxygenases and Prostaglandins in the Central Nervous System. *Molecular Neurobiology*, 53(7), 4754-4771. doi:10.1007/s12035-015-9355-3

- Yaicharoen, P., Wallman, K., Bishop, D., & Morton, A. (2012). The effect of warm up on single and intermittent-sprint performance. *Journal of Sports Sciences*, 30(8), 833-840. doi:10.1080/02640414.2012.675084
- Young, A. J., Sawka, M. N., Epstein, Y., Decristofano, B., & Pandolf, K. B. (1987). Cooling different body surfaces during upper and lower body exercise. *Journal of Applied Physiology*, 63(3), 1218-1223.
- Zamparo, P., Cortesi, M., & Gatta, G. (2020). The energy cost of swimming and its determinants. *European Journal of Applied Physiology*, 120(1), 41. doi:10.1007/s00421-019-04270-y